Combined Effect of Sea-Level Rise and Coastal Land Subsidence – Identification of Critical Transportation Infrastructure At-Risk in Coastal SPTC Region

Part I – Coastal Louisiana

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The coast of Louisiana is under threat because of sea-level rise and land subsidence. Seawater is encroaching deeper inland and as a result Louisiana is losing at an alarming rate. The combined effect of sea-level rise and land subsidence is variable spatially. This report focuses on this combined effect in identifying the transportation infrastructure that is at risk of getting affected by the sea-water inundation of the land. This report takes account of land elevation data monitored continuously at various locations along the coasts of Louisiana and combining it with local sea-level rise to arrive at the extent of land that will be lost because of rising seawater. GIS was used to process the collected data, put it in spatial format and identify the transportation infrastructure that is at risk for next 100 years, with 10-year increments starting from 2014. Open-source data made available by federal agencies was processed using ArcGIS to develop spatial surfaces and intersect those surfaces with transportation data. The results suggest that land subsidence in Louisiana is having greater impact on transportation infrastructure than sea-level rise. It is projected that by year of 3014, about 2,945 miles or 21% of the existing transportation infrastructure will be impacted because of the combined effect of land subsidence and rising sea level. This estimate does not take account of effectiveness of extensive levee system present in parts of coastal Louisiana.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Part 1 – Coastal Louisiana

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SUMMARY

The coast of Louisiana is under threat because of sea-level rise and land subsidence. Seawater is encroaching deeper inland and as a result Louisiana is losing at an alarming rate. The combined effect of sea-level rise and land subsidence is variable spatially. This paper focuses on this combined effect in identifying the transportation infrastructure that is at risk of getting affected by the sea-water inundation of the land.

This paper is an attempt of taking account of land elevation data monitored continuously at various locations along the coast of Louisiana and combining it with local sea-level rise to arrive at the extent of land that will be lost because of rising seawater. GIS was used to process the collected data, put it in spatial format and identify the transportation infrastructure that is at risk for next 100 years, with 10-year increments starting from 2014. Open-source data made available by federal agencies was processed using ArcGIS to develop spatial surfaces and intersect those surfaces with transportation data. The results suggest that land subsidence is having greater impact on transportation infrastructure than sea-level rise. It is projected that by year of 3014, about 2,945 miles or 21% of the existing transportation infrastructure will be impacted because of the combined effect of land subsidence and rising sea level. This estimate does not take account of effectiveness of extensive levee system present in parts of coastal Louisiana.

INTRODUCTION

Transportation infrastructure is critical for the social and economic growth of any region and nation. It requires a major investment in terms of capital and efforts to provide and maintain adequate and efficient long-term transportation of material and people. As population grows and economic opportunities increase, so does the reliance on the infrastructure that supports this growth. Protecting existing transportation assets and planning for new and more effective transportation infrastructure requires forecasting of risks from dangers of climate change and extreme weathers. It is for this reason, state and federal transportation agencies focus on susceptibility and resiliency of existing transportation assets in regions that are more prone to these risks.

The transportation infrastructure in southern Louisiana provides essential routes of evacuation during storms for a population of more than three million. The transportation infrastructure also serves the nation's energy needs. The majority of Louisiana's population is in the southern and coastal region. Additionally, industrial and commercial activities make this region even more important. Louisiana's energy industry is one of the largest in the nation. Louisiana is second only to Texas in crude oil distillation capacity, refining approximately 3,343,206 barrels per calendar day. The state is also home to two of the five largest refineries in the country (1). In 2011, the Department of Homeland Security reported findings in which it estimated that a 90-day closure of Highway 1, which is logistically critical for the transportation of oil and natural gas would cost the nation 7.8 billion dollars (2). The energy industry is not the only industry with a national impact. Agriculture accounts for billions of dollars in revenue for the state. Louisiana has one of the largest and most diverse aquaculture industries in the nation which ranks third in commodities values. The state is also one of the most abundant rice and sugar cane producers in the country (3). Much of this economic activity takes place within southern Louisiana.

There are nearly 14,000 miles of federal and state routes in southern Louisiana, not including street-level routes. In parts of coastal Louisiana, the transportation infrastructure may lie at or below sea level. A sophisticated and critical levee infrastructure is in place to protect all aspects of the activity in southern Louisiana from storm surges, ocean waters, and flooding while also controlling the flow of the Mississippi River. A portion of the levee system can also be used for transportation.

The coast of Louisiana is under threat because of sea-level rise and land subsidence. The rate and the extent of the land that has been lost to sea in coastal Louisiana point to the ever-growing problem of encroachment of seawater deeper inland. The combined effect of sea-level rise and land subsidence in this region has worsened the problem significantly. The effects vary spatially along the coast of Louisiana because of several local parameters such as regional ocean currents, land subsidence, and erosion. Rising sea levels are driven by both increased warming of oceans and ground subsidence (4, 5). Many locations in coastal Louisiana including New Orleans and gulf coast, in general, are extremely vulnerable to the impacts of sea-level rise as shown in **Figure 1**. The observed changes in sea level relative to land elevation at these locations were found to be more than 8 inches between 1960 and 2014 (6). It is projected that sea level will rise more rapidly throughout the rest of this century and is expected to exacerbate existing threats in this region (4).

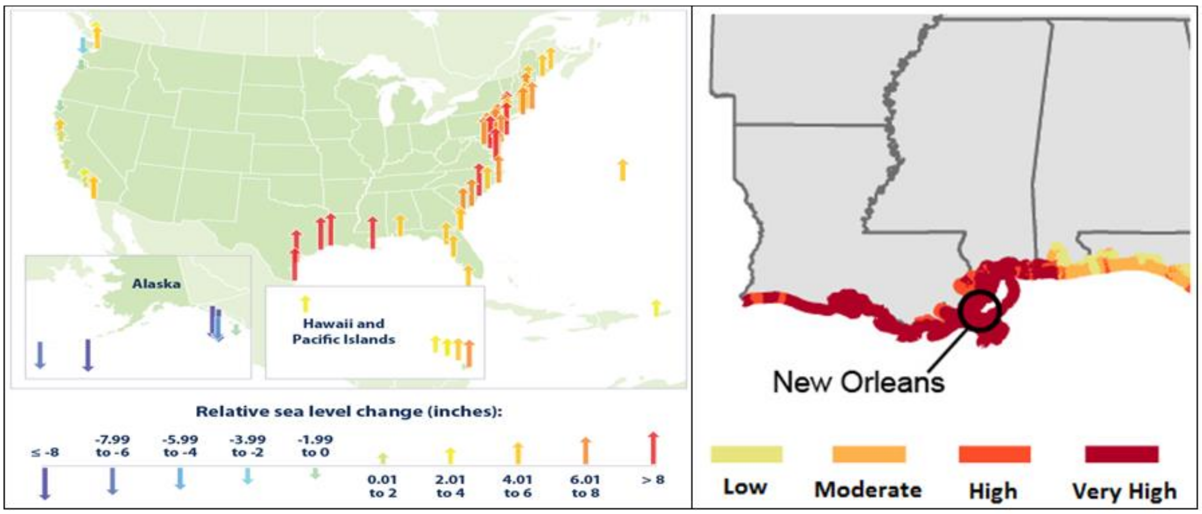

Figure 1. Left: Observed changes in sea level relative to land elevation in the United States between 1960 and 2014 (6). Right: The levels of risk sea level rise poses along Louisiana's coastline, taking into consideration the susceptibility to change and adaptation measures (4).

According to the National Aeronautics and Space Administration (NASA) the seas are getting warmer. It estimates that the global rate of sea-level rise is at 3.2 mm per year (7). As sea levels along the coast are rising, land subsidence in many areas is increasing. The increasing temperature of the oceans can cause the greater strength and frequency of storms leading to even more significant coastal erosion and flooding. This is not only a problem for Louisiana but also large parts of the south and east coast of the United States.

The land subsidence may happen because of natural reasons such as limestone bedrock dissolution or drainage and degradation of organic soils in some parts of the United States (8). It could also be a result of anthropogenic activities such as the extraction of both water and petroleum resources. Theoretically, land subsidence is defined as a decrease in soil volume by compaction. It decreases the land elevation. As the elevation in southern

Louisiana decreases its risk for inundation increases. Intense rainfall, storm surge, rising sea level, and levee breaches are the main factors that contribute to inundation of the subsided land. Subsidence also reduces the heights of the levee infrastructure endangering the protected areas. In addition, land subsidence can cause a reduction in soil porosity which can decrease soil water retention, infiltration, and percolation. This can lead to higher runoff and prolong water accumulation on the surface. While land subsidence is one critical factor influencing coastal Louisiana in a negative way, it is not the only factor.

The rising sea level is another factor that has impacted coastal areas even more. The sea-level rise is the result of climate change and is occurring across the globe. Within the continental United States, the coast of Louisiana is experiencing some of the worst sea level rises. The combined impacts of sea-level rise and land subsidence are jeopardizing not only the geography of coastal Louisiana but also its population. As land subsides and the sea level rises the natural and man-made barriers are either lost to submergence or lose their ability to protect the region.

This paper takes account of historical land elevation and sea level data in forecasting the overall effect on critical transportation infrastructure in southern Louisiana. The rate of land subsidence and sea-level rise were calculated based on the past data and their combined effects were projected into future (short-term and long-term) to determine the extent of the sea encroachment and identification of impacted transportation infrastructure. Geographic Information System (GIS) was used as a tool to identify the transportation structure at risk. Open-source data made available by regional and federal agencies were used in ArcGIS to develop GIS surfaces (layers). These surfaces were then intersected with spatial transportation data. The overall process and results are discussed in this paper. A detailed description of steps involved in data processing, as well as the overall approach adopted, is provided as a base reference to be adopted for other similar studies.

OBJECTIVE

To achieve the project goal, we will pursue the following specific objectives:

i) Investigate the land subsidence trend spatially along the coast of Louisiana.

ii) Investigate the sea level rise and combined it spatially with spatial land subsidence.

iii) Investigate and identify transportation infrastructure that is at risk because of the combined effect of sea-level rise and land subsidence based on the forecasted trend in the coastal region.

SCOPE

The scope of the project includes evaluating the trend of sea-level rise and land subsidence from the data that is collected by various federal and state agencies and use it to delineate areas that are expected to be flooded in long term. The identification of transportation infrastructure impacted by the combined effects did not consider the effectiveness of the extensive levee system in parts of coastal Louisiana.

The extent of the study area is covered by 27 southern parishes of the state of Louisiana. These 27 parishes are home to nearly 7/10 of Louisiana's population, billions in monthly commerce at the national and state level, and thousands of miles in transportation infrastructure. The extent also includes many of Louisiana's major urban areas such as New Orleans, Baton Rouge, and Lafayette. The extent of the study area is displayed below in **Figure 2**.

Figure 2. Study area extent.

METHODOLOGY

GIS Approach

GIS as a tool can be incredibly insightful in researching both subsidence and sea-level rise. It offers platforms in which various spatial data formats can be processed, manipulated, integrated, analyzed, and interpreted. This allows researchers and users a greater understanding of the data such as relationships and patterns that, otherwise, may not have been observed. The patterns or relationships present in the data can be projected in visual forms offering meaningful insight.

This research was conducted with ArcGIS utilizing its Spatial Analysts extension to create projected inundation shapefile. This shapefile was used in creating another shapefile identifying the impacted transportation infrastructure because of various projected (forecasted) inundation. The datasets were generated by interpreting, analyzing, amending, and integrating data from numerous federal agencies. The specific and detailed approach is presented in the "Methodology" section of this paper. The authors have been applying GIS to solve various challenges related to transportation in coastal region. Previously, similar fundamental GIS approach was used in identification of geological zones in coastal Louisiana that have varying degrees of corrosive soils for metal pipes. The results that were accepted by the Louisiana Department of Transportation and Development (LADOTD) were presented at various national conferences and published accordingly (9-13).

Sources, types, and processing of data

The source data was gathered from the four federal agencies. The following section details the sources, processing, and use of the data. The data from all four agencies were projected from their sourced coordinate systems to NAD 1983 State Plane Louisiana South before any of the processing outlined below took place. The process and various steps are described for the sake of accuracy and to outline an approach that could be adopted with stated benefits for similar projects in the future. Also, it is essential that even the minor details of each and every step is provided for researchers to reproduce results or apply this method as accurately as possible to completely new set of data.

The NOAA Data

The *Topobathymetric Model of the Northern Gulf of Mexico* is a dynamic, multi-sourced, and highly accurate topobathymetric digital elevation model (TBDEM). The model is a result of the integration of topo and bathy LiDAR, hydrographic surveys, side-scan sonar surveys, and multibeam surveys (*14*). The period of data collection is from 1988 to 2013 with the topo

LiDAR collections of coastal Louisiana being the most recent. The resolution of the dataset ranges from 1 to 3 meters with vertical accuracy between 6 and 23.5 centimeters (*14*). The dataset in its original and unaltered state is displayed below in **Figure 3-A**.

The TBDEM was refined to match the extent, increase processing speed, and correct minor issues in delineations of the water surface elevation before it was used for the development of the inundation shapefiles. The TBDEM was matched with the study area extent by running the "Extract by Mask" tool using the processed Census Bureau TIGER/line county shapefile as the feature mask data. The resulting TBDEM is displayed in **Figure 3-B**. It was followed by resampling of TBDEM from a 3-meter resolution to 9.144-meter. The resampling and extraction decreased the storage size of the data and increased the processing speeds for many of the steps required to create the inundation shapefiles. The final refinement needed seven areas in TBDEM to be "hydro-flattened" where the water surface elevations were slightly off from neighboring water surfaces as displayed in **Figure 3-C**. These discrepancies were a result of the classification of water heights in the initial LiDAR datasets that were collected at different times. If LiDAR datasets were processed during periods of higher water levels, it would increase the water level heights while LiDAR datasets from the neighborhood would have different water elevation if collected at a different time of the day. All the discrepancies occurred in the wetlands or marshes of southern Louisiana and were corrected to 0-meters in elevation; this was the water height for the surrounding areas.

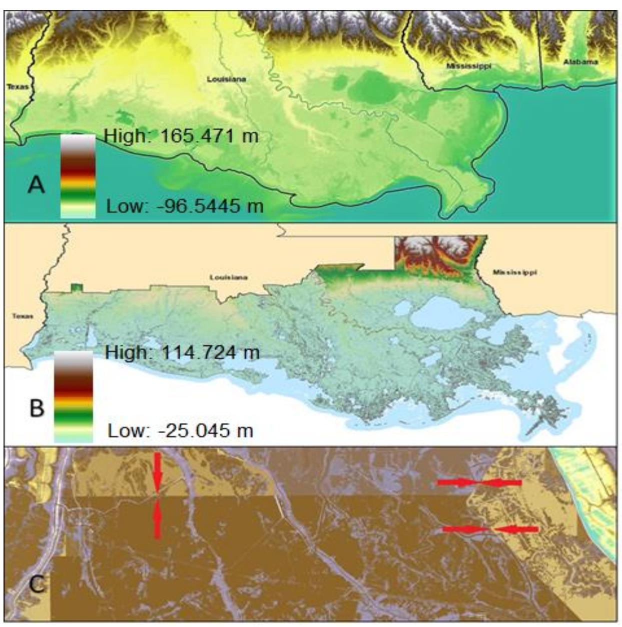

Figure 3. A) TBDEM of the Northern Gulf of Mexico. B) Extracted TBDEM. C) Example of water elevation discrepancies.

Once the preparation of the TBDEM surface was completed, it was ready for the required processing to create the inundation shapefiles. This dataset is the zero-day elevation surface to project the impacts of subsidence and sea-level rise. The dates represented in the corresponding maps are projected from the 2014 release date of the TBDEM. The effects of land subsidence and sea-level rise were forecasted up to 100 years with ten-year intervals. The areas residing below 0-meter in elevation were extracted and classified as potentially at-risk areas for inundation. The impact levees would have in protecting these potentially at-risk areas and keeping them from getting submerged needs to be investigated specifically and for this reason, they are classified as “potentially at risk”.

The NGS Data

Continuously Operating Reference Station (CORS) datasheets and their corresponding shapefiles are a collection of surveying grade geodetic information over a benchmark (CORS station). Surveying benchmarks and CORS shapefiles of the state of Louisiana were downloaded from the NGS download page. These shapefiles were clipped to the study area extent using Census Bureau TIGER/line county shapefile displayed above in **Figure 1**. The shapefiles were then edited to only keep ObjectID, Shape, PID, Designation, Latitude, and Longitude attribute fields. The edited CORS and benchmark shapefiles were merged into one single shapefile. The orthometric heights of each CORS location were calculated and compared using their PID and datasheets with current and suspended survey controls using 2004.65, 2006.81, and 2009.55 epochs. This process resulted in 112 locations used as reference points across southern Louisiana.

The subsidence rates per year of these locations were calculated in Excel from the change in their respective elevations with time as observed in the NGS data. The values were tracked using PIDs, designations, and recorded orthometric height for each epoch. The subsidence per year was multiplied with the desired time period in years (with 10-year intervals) to calculate the projected (forecasted) elevations up to the next 100 years. The Comma Separated Version (CSV) version of this Excel file was joined to the edited NGS shapefile using the PID fields. The joined shapefile was then exported to a separate shapefile retaining all the information of both the NGS shapefile and the excel table.

Once the preparation of the NGS survey marks and CORS was completed, each location retained information for its rates of subsidence. These rates were used to interpolate ten raster surfaces reflecting the rate of subsidence for each ten-year interval. Those raster surfaces were then applied to the TBDEM surface which resulted in ten separate TBDEM surfaces impacted by forecasted subsidence. Those surfaces then had the ten-year interval predicted impacts of sea-level rise applied to them.

The NASA Data

Global sea-level rise rate was obtained from NASA website. Global sea-level rise rates are observed based on satellite observations of sea level compiled at the NASA Goddard Space Flight Center (*15*). The rate of sea-level rise used for this study was 3.2 mm/year. The appropriate unit conversion was performed and the desired time period (in years) was multiplied to calculate the projected sea-level in the future.

During processing for the inundation datasets, the recorded sea-level rise values are applied to the subsided LiDAR surfaces using the Raster Calculator. The resulting LiDAR surface had the combined impacts of both subsidence and sea-level rise.

United States Census Bureau Data

The United States Census Bureau maintains large geographic datasets that range from congressional districts to water boundaries. Topologically Integrated Geographic Encoding and Referencing (TIGER) is one such GIS dataset. There are multiple TIGER datasets and formats. The most comprehensive TIGER GIS data offered is the TIGER/Line shapefiles (*16*). The Census Bureau has a web interface under its geography section for downloading GIS data. TIGER data is continuously updated and checked for accuracy.

Three shapefiles were used for both the preparation of data and for the processing of the inundation of land and the inundation of transportation infrastructure shapefiles that were derived from the Census Bureau. These shapefiles were the counties, water boundaries, and the primary and secondary roads. First, the "counties" shapefile was exported based on the 27 selected parishes that set the extent of the study area. The resulting shapefile was then clipped to match the current geography of southern Louisiana. The water boundaries were erased from the resulting shapefile. The water boundaries and primary and secondary roads required clipping to match the extent of the study area. Once the Clip was completed the water boundaries needed no additional refinement. The primary and secondary roads required one extra step - dissolving of the shapefile by the name field.

The counties shapefile was used for masking any processing such as the clips or interpolations required in the preparation of data and processing for the inundation shapefiles. The dataset was also used as the feature mask data for all the Extract by Mask processes ran on the raster surfaces. The primary and secondary roads were intersected with each inundation shapefile to create the inundation of transportation infrastructure shapefile. All the shapefiles were used for cartography purposes.

Data Processing and Forecasting the Combined Effect of Land Subsidence and Sea Level Rise

Once the data was processed, the groundwork was set for the development of both the inundation shapefiles and the inundation of transportation infrastructure shapefile. The goal was to develop accurate inundation shapefiles which would be used to modify the TIGER/Lines primary and secondary roads shapefile to create a single inundation transportation shapefile. The goal of inundation transportation infrastructure dataset was to reflect and categorize segments of essential routes in coastal Louisiana that may be at risk by the combined effect of land subsidence and sea-level rise.

The processing was organized into four separate phases. The separation aided in monitoring progress, addressing errors as they happened, and data storage. Having the ability to resolve errors saved substantial time in processing large datasets such as the TBDEM of the Northern Gulf of Mexico and its outputs. Each phase resulted in a minimum of ten outputs that may have only been critical to the next process or phase. That means that there was a significant amount of data both in storage size and quantity to keep organized and achieved as the processing proceeded. The data storage was structured within folders corresponding to phases with subfolders corresponding to the processes.

The methodology phases correspond to their major purpose(s). The first phase was the interpolation of the amended National Geodetic Survey (NGS) data. In this phase, raster surfaces were created with values reflecting predicted rates of subsidence that would occur at specific intervals and locations. The second phase was the calculation of subsidence and sea-level rise. In this phase, the impacts of both subsidence and sea-level rise were applied to the TBDEM surface. The third phase was extraction, conversion, and classification. In this phase, the areas impacted within the raster surfaces are extracted, converted to shapefile, and classified by their predicted year of inundation. The integration of values from the inundation shapefiles to the TIGER/Lines primary and secondary roads shapefile was done in the fourth phase to identify the impacted infrastructure. During this phase and only during this phase, all processes were not duplicated ten times. The result of this phase would be only one shapefile. The procedures for each phase were constructed in ArcMap ModelBuilder for visual reference. The phases of processing are depicted in **Figure 4**.

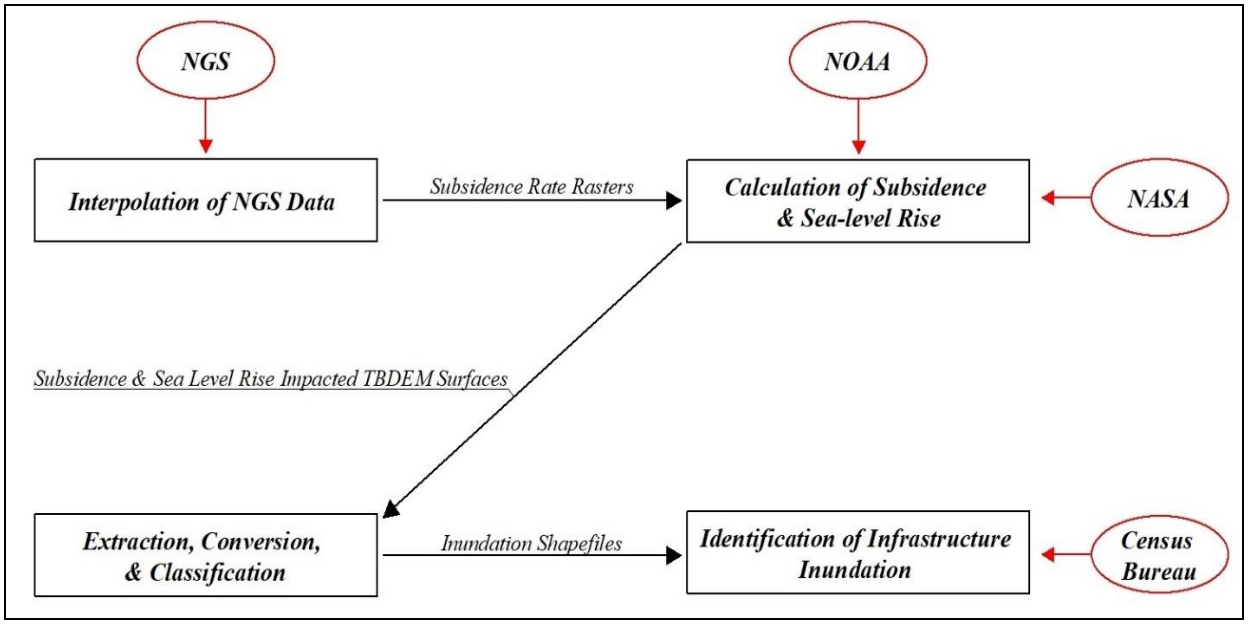

Figure 4. Phases of data processing.

Interpolation of NGS Data

As shown in **Figure 4**, the interpolation of the amended NGS data was the first phase of the processing. The ModelBuilder was used to save time. The data interpolation was done 10 times with 10 separate attributes using the Inverse Distance Weighted (IDW) tool in Spatial Analyst toolbox. The interpolation was executed for each 10-year interval by changing the Z value field, for the amended NGS data it was the subsidence values for each 10-year interval. The number of points in the search radius was decreased from 12 to 6. IDW calculates weighted averages of surrounding values to determine values at non-sampled locations and the influence of each location decreases as the distance from that location increases. Land subsidence is highly localized and for this reason, IDW was the best choice for interpolation. To further increase the tool's localization, the number of points of the search radius was limited to 6. The reminding parameters were set in the model properties menu under environments.

The model had three parameter sets. The output coordinate system was set to *NAD 1983 2011 State Plane Louisiana South FIPS 1702 Ft US*. The next two parameter sets were both raster analysis. The cell size was set to the TBDEM surface (9.144 meters), and the mask was set to the processed TIGER/Lines counties shapefile. The sequence of steps is shown as a flowchart in **Figure 5-A**.

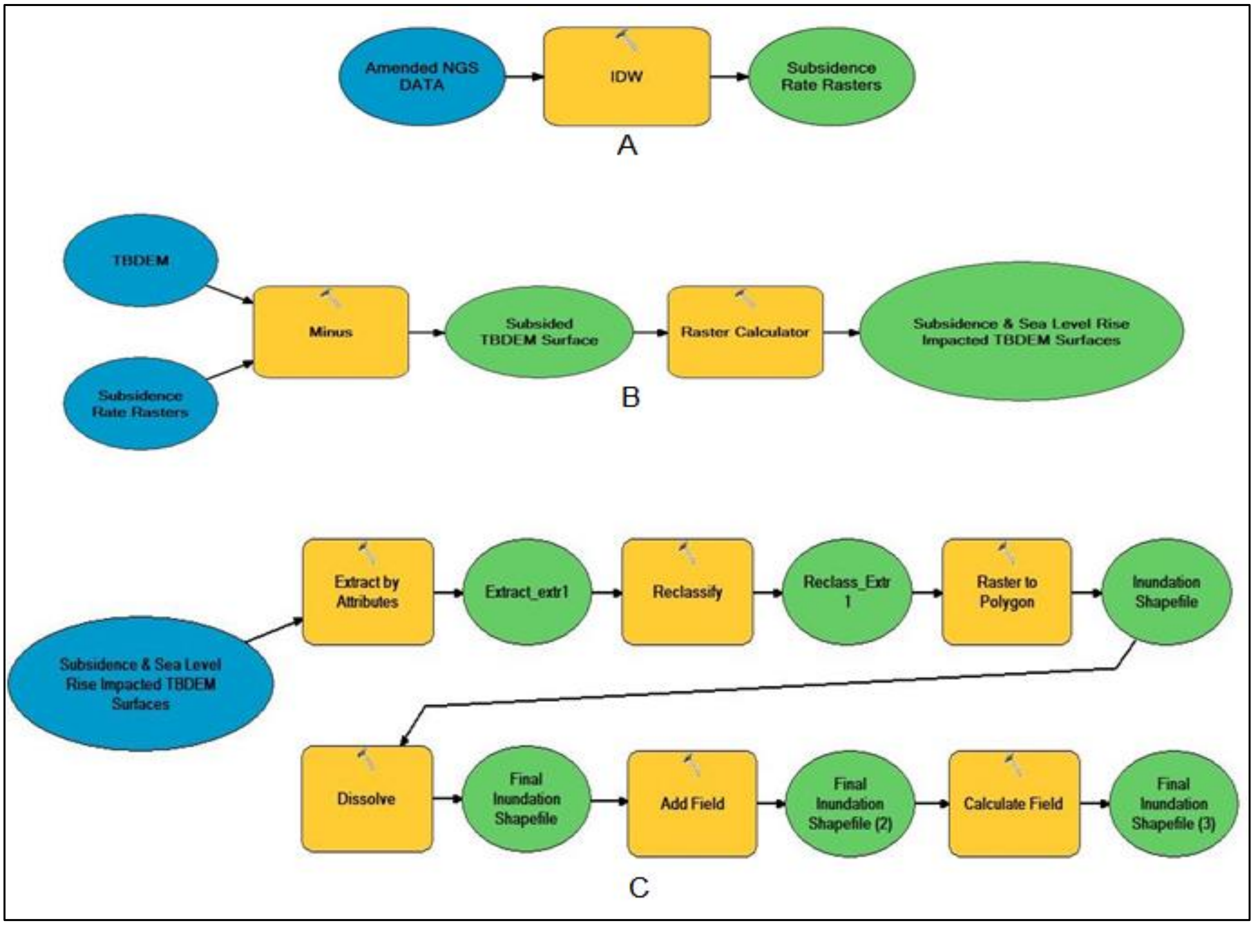

Figure 5. The sequence of steps for - A) Interpolation of NGS data. B) Calculation of subsidence and sea-level rise. C) Extraction, conversion, and classification.

Calculation of Subsidence and Sea-level Rise

In the second phase of processing as shown in **Figure 4**, the impacts of subsidence and sea-level rise were applied on the TBDEM surface by incorporating the subsidence rate rasters and the NOAA sea level rise information. The subsidence rate rasters were subtracted from the TBDEM surface ten times (one for each 10-year interval) creating 10 subsided TBDEM surfaces using the Minus tool in the Spatial Analysts toolbox. The Minus tool subtracts the values of one raster from another raster. The constant value 1 raster was set to the TBDEM surface for each of the 10 processes, making it the raster from which the other rasters will be subtracted. The "constant value 2" raster was set to one of the 10 different subsidence rate rasters for each process. The "constant value 2" raster will be the value subtracted from the "constant value 1" raster. Following this, rates of sea-level rise were applied to each of the ten subsided TBDEM surfaces. It was accomplished using the Raster Calculator tool in the

Spatial Analysts toolbox. In the map algebra expression box of the Raster Calculator, the sea level rise (calculated from the NASA sea lever rise sate) were subtracted from each correlating subsided TBDEM surface. For example, a subsided TBDEM surfaces of 40 years should have 0.128 m subtracted from it, 0.128 m being the 40-year projected global projected sea-level rise in meters. The resulting TBDEM surfaces from both processes had both impacts of subsidence and sea-level rise applied to them. The reminding parameters for both processes were set in the model properties menu under environments.

The model had two parameters set. The output coordinate system was set to *NAD 1983 2011 State Plane Louisiana South FIPS 1702 Ft US*. The next was setting the cell size to the TBDEM surface (9.144 meters) under raster analysis. The sequence of steps is shown as a flowchart in **Figure 5-B**.

Extraction, Conversion, and Classification

The third phase of the data processing as shown in **Figure 4**, extracted the areas at risk of inundation from the subsidence and sea-level rise impacted TBDEM surfaces, converted these rasters to shapefile, and added an identification attribute to the shapefiles. The processes were repeated for each 10-year interval. The first process was to extract the areas that were at risk of inundation due to residing below 0-meter of elevation for each of the subsidence and sea-level rise impacted TBDEM surfaces. The TBDEM surface processed for this research classifies the water surface elevation in the wetland and marshes along the coast as 0-meter or less in elevation. This process was accomplished using the Extract by Attributes tool in the Spatial Analyst toolbox. The Extract by Attributes tool uses a logical expression to extract values of a raster. The expression used to extract the values below 0-meter of elevation was “VALUE” < 0.000001. Following this, the data was reclassified. The elevation of the extracted surfaces inherited the extensive range of values of the TBDEM surface which would generally slow or stop any processing of the inundation shapefiles. The Reclassify tool changes any values of a raster. The reclass field was set to values. In the reclassification table, the old values column was set to the lowest elevation of the TBDEM surface to the limit set in the logical expression used for the Extract by Attributes tool (-405.238 - 0.000001). The new value was set to 0. This will reclassify all the elevation values of the extracted surfaces to 0. The NoData environment setting was used to change missing values to no data. It resulted in all values below 0.000001 being classified as 0 or no data. The next process was to convert the reclassified raster to a shapefile. This process was accomplished using the Raster to Polygon tool in the Conversion toolbox. The only parameter set for this tool was checking the simplify polygons box. The next process was to dissolve the newly created inundation shapefiles. The dissolve aids in decreasing the storage space and attributes of the inundation shapefiles which helped minimize the shapefiles rendering time. The only parameter used was checking the “create multipart features” box. The next two processes were to create an identification attribute for each inundation shapefile. The addition of a specific identification attribute is necessary for the creation of the inundation of transportation infrastructure shapefile in the next phase. First, a field had to be added to the attribute table of each inundation shapefile. This was accomplished using the Add Field tool in the Data Management toolbox. The field name and field type tool parameters were set. The field name was labeled *IId* for inundation identification and the long for the field type. Next, the newly created field had to be calculated. This was accomplished using the Calculate Field tool in the Data Management toolbox. To calculate the field, the field name used for was set to *IId* for each inundation shapefile. In the expression box, the numerical value was set to the interval year of shapefile being identified. An example of this would be the 50-year interval inundation shapefile with the numerical value 50 in the expression box. The remaining paraments were set in the model properties menu under environments.

The model had two parameters set. The output coordinate system was set to *NAD 1983 2011 State Plane Louisiana South FIPS 1702 Ft US*. The next was setting the cell size to the TBDEM surface (9.144 meters) under raster analysis. The sequence of steps is shown as a flowchart in **Figure 5-C**.

Identification of Infrastructure Inundation

The final phase of processing was to identify portions of the transportation infrastructure that are at risk of getting impacted by the encroaching seawater. It was achieved by intersecting transportation infrastructure shapefile with the inundation shapefiles. The series of actions presented in **Figure 6**, is just a visualization example of the steps and tools used for the processing of the first 40 years of inundation. The complete series of steps would require all 100 years or 10 inundation shapefiles (one of each 10-year period). The final aspect was the consideration of the Intersect and Spatial Join tools. The Intersect tool which is found under the Analysis toolbox calculates the geometric intersection of multiple shapefiles producing one shapefile with whose attributes contain this relationship. The Spatial Join tool is in the same toolbox directly next to the Intersect. The Spatial Join tool will join the attributes of one shapefile to another based on their shared spatial relationship. The two tools which may share results in some cases that are similar do not share the same functions. In this research, the Intersect tool was used for processing because of its functional use in developing and maintaining the geometric relationship of the “TIGER/Line primary and secondary roads shapefile”. This allows for the addition of accurate geometric attributes such as length, bearing, height, and other geometric characteristics to the attribute fields of the inundation of transportation infrastructure shapefile.

The processing for this phase begins with the use of the Intersect tool. The input features were the TIGER/Line primary and secondary roads and one inundation shapefile. The only parameter changed from the tool's default was the join attributes field which was No FID. The tool was run ten separate times for ten outputs, one for each inundation file with an increment period of 10 years. The ten resulting line outputs were segments of the TIGER/Line shapefile impacted by the different inundation shapefiles which all contained *IId* fields which were merged. The merged shapefile was then used to erase the inundated segments of roads from the TIGER/Line shapefile. This was achieved by using the Erase tool. The input feature for this tool was the TIGER primary and secondary roads and the erase feature was the merged inundated roads. The output of this process is a shapefile containing all roads that will not be impacted because of projected inundation resulting from the combined effect of land subsidence and sea-level rise. At this time stage of the processing, there were two shapefiles, one with roads that are potentially impacted by subsidence and sea-level rise and other with roads that are not going to be impacted. The next process was to combine these two shapefiles into one shapefile which will provide a complete picture of the future state of the transportation infrastructure. The Merge tool was used for the second time during this process to attain the final inundation of transportation infrastructure shapefile. The Dissolve processes displayed in the model below are not required but they will improve the organization of the attribute table for the final shapefile.

A visual summary of this phase is presented as an example in **Figure 6**. It would only require one parameter to be set, setting the output coordinate system to *NAD 1983 2011 State Plane Louisiana South FIPS 1702 Ft US*.

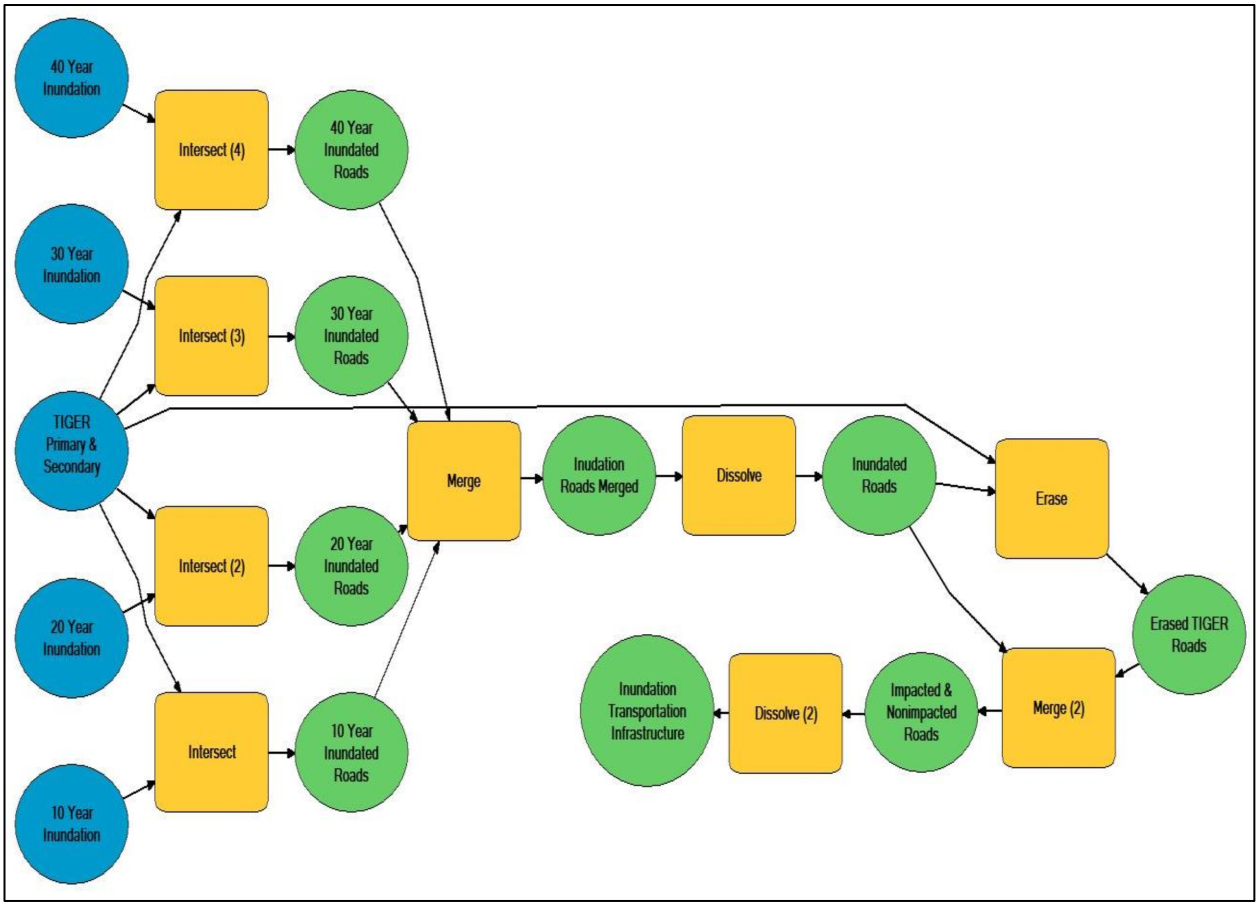

Figure 6. Identification phase of impacted infrastructure because of Inundation.

DISCUSSION OF RESULTS

The final results of the overall process were eleven shapefiles (10 inundation shapefiles and one shapefile with impacted transportation infrastructure because of inundation). These shapefiles were used for the analysis and mapping of the impacts of land subsidence and sea-level rise on coastal Louisiana and its transportation infrastructure. One must understand that the total length of the TIGER/Line primary and secondary roads in southern Louisiana was about 13,916 miles. It only accounted for major federal and state highways. Also, the total area of the TIGER/Line county shapefile, clipped to the geographic extent of southern Louisiana and had the water bodies erased from it, was about 15,785 square miles. The measurements of the length and area of these shapefiles are accurate, but it is important to remember that these shapefiles are approximating the geography and transportation infrastructure. Finally, the resulting shapefiles do not account for the protection provided by the levee infrastructure for the reason as discussed previously in this paper.

The inundation shapefiles revealed that there is a strong trend of land loss due to land subsidence and sea-level rise in southern Louisiana. Land subsidence has a greater impact than sea-level rise. The first 10 years of inundation reveal a total land loss of about 2,130 square miles which is 13% of the original geography. It consists of one major metropolitan area, New Orleans with nearly half of its area being below 0-meter in elevation (sea level). This number may not be accurate as New Orleans has extensive levee system protecting from sea level rise. When forecasted to next 100 years starting from 2014, the date of the source surface elevation, the land loss is far greater. The cumulative 100 years of inundation reveal a total land loss of about 8,405 square miles which is 53% of the original geography. By year 3014, the seawater would reach far north and could threaten small portions of Lake Charles, Lafayette, almost all the Atchafalaya floodplain and its surrounding area south of Baton Rouge. The wetlands along the coast would also be impacted with the exceptions of the levees which lost elevation but remain high enough that they would not be submerged. The inundation shapefiles were used to create ten separate maps of 10-year intervals projecting out from 2014. In the maps, the red regions symbolize potential inundation. The 10-year and 100-year projections are presented in **Figures 7** and **8**.

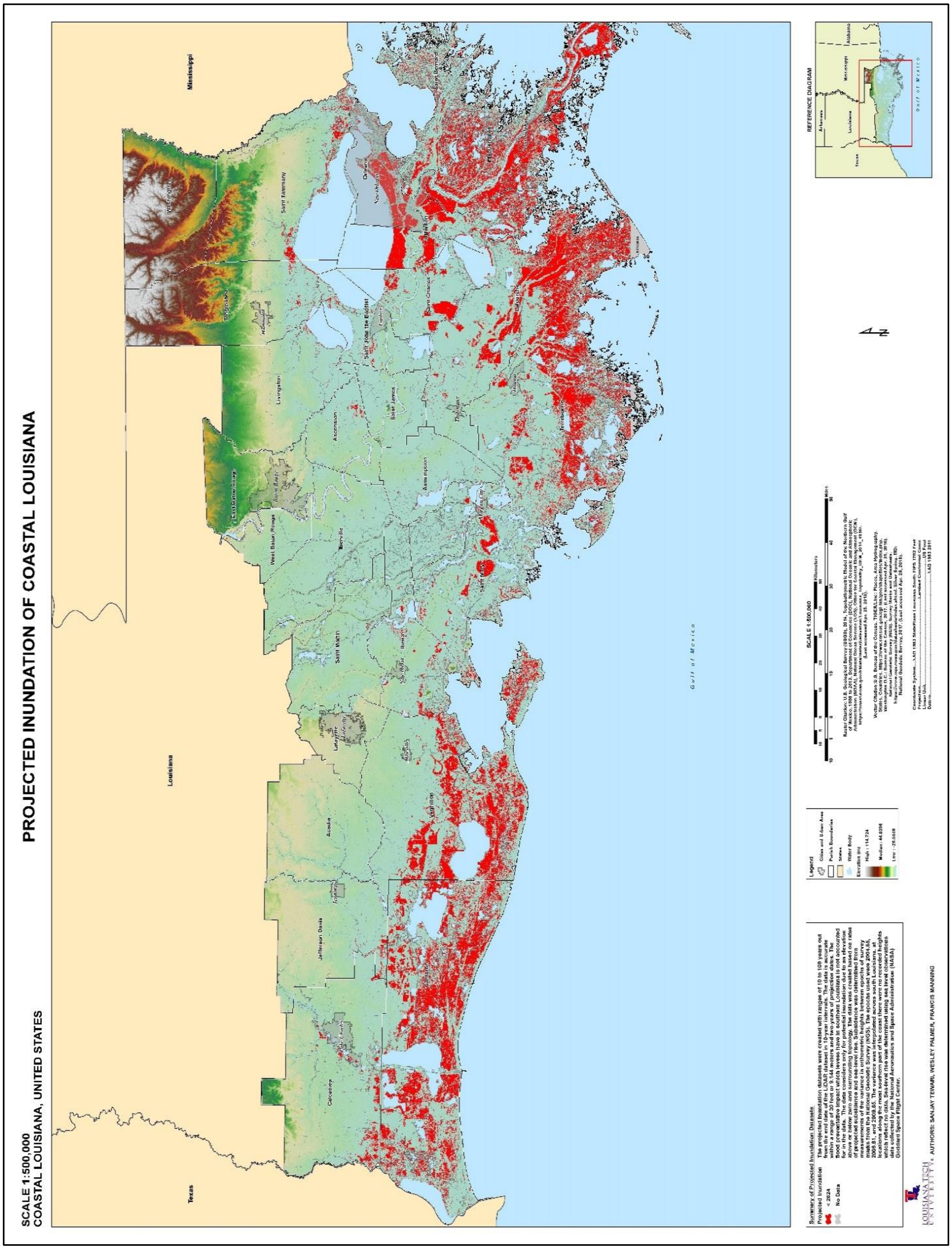

Figure 7. Map of 10-year projected inundation of coastal Louisiana.

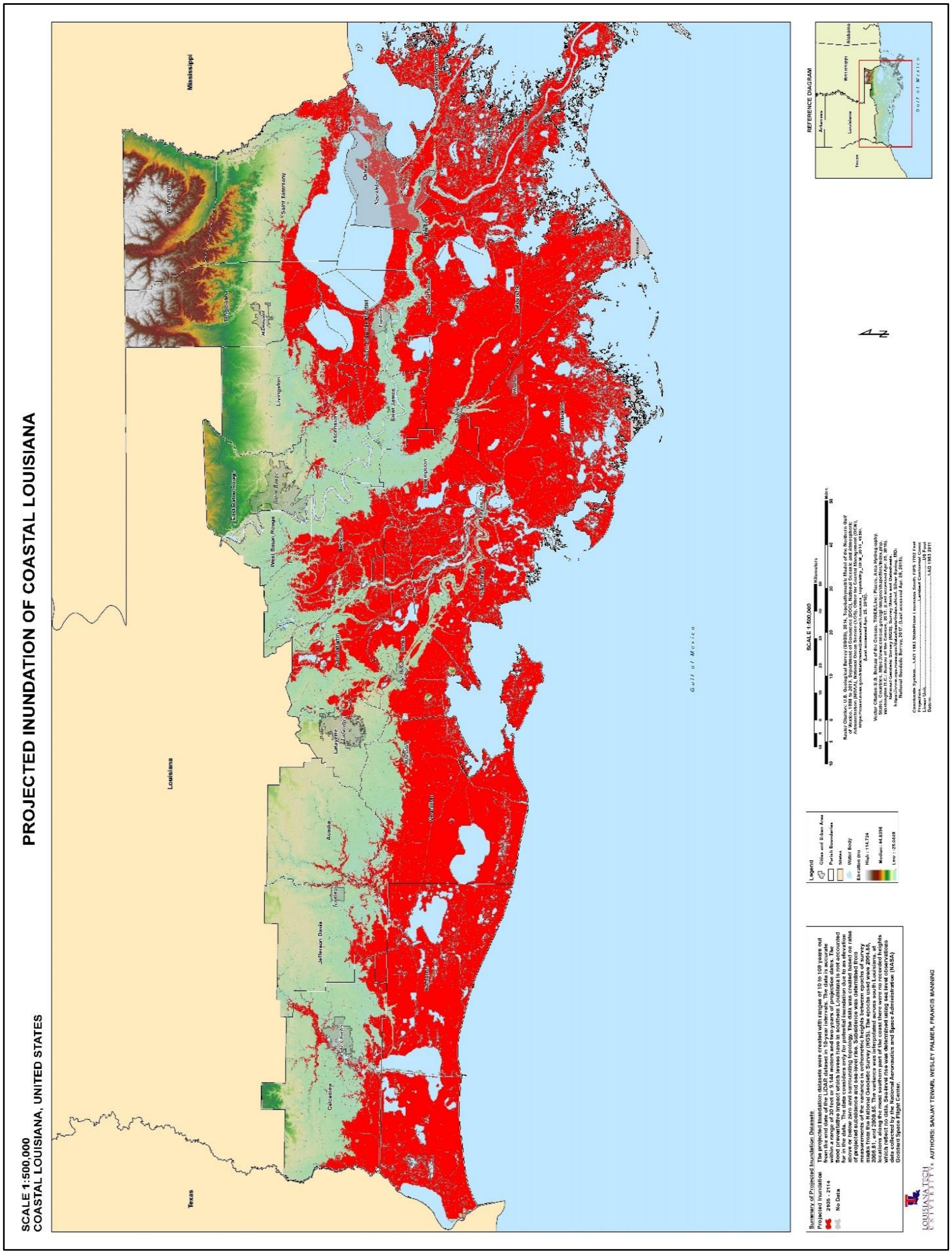

Figure 8. Map of 100-year projected inundation of coastal Louisiana.

The inundation of transportation infrastructure shapefile revealed that there is a very strong likelihood of transportation infrastructure loss due to land subsidence and sea-level rise in southern Louisiana. The first 10 years of inundation reveal a total loss of about 423 miles of infrastructure which is 3% of the original transportation infrastructure. This is the greatest loss of infrastructure for any of the ten 10-year intervals. Part of the reason for this is that the dataset is accounting for infrastructure that is already residing below 0-meters in elevation such as infrastructure in the greater New Orleans metro area. After this period the infrastructure loss averages 2% per every 10-year interval ranging from 125 to 345 miles of the total loss. By 100 years the projected loss of infrastructure due to inundation is about 2,945 miles or 21% of the original infrastructure. **Table 1** outlines the mileage and percentages of transportation infrastructure lost over 100 years.

Table 1. Projected loss of transportation infrastructure.

Projected Years	Total Infrastructure Loss (Miles)	Percentage of Loss
10	422.92	3%
20	125.40	1%
30	236.56	2%
40	283.15	2%
50	322.07	2%
60	344.94	2%
70	324.33	2%
80	321.96	2%
90	290.04	2%
100	272.83	2%
TOTAL	**2944.20**	**21%**

The inundation of transportation infrastructure shapefile was then used to create an indexed map book detailing the potential impact of subsidence and sea-level rise on the transportation infrastructure. The map book consists of 63 pages (a cover page and 62 map sheets). The inundation of transportation infrastructure shapefile was symbolized based on 20-year intervals. The cover page and an example of one of the map sheets are presented in **Figures 9** and **10**.

It is hoped that the method described and the results obtained in this study will be used by LADOTD in long term planning for challenges associated with climate change. It will also provide a mechanism to forecast the effects of similar changes on transportation infrastructure. Additionally, if a reference elevation is needed to simulate extreme storm surge of any proportions, this study could be used as a base and additional storm surge can be added to inundation layers appropriately to map out the extent of the area that will be impacted.

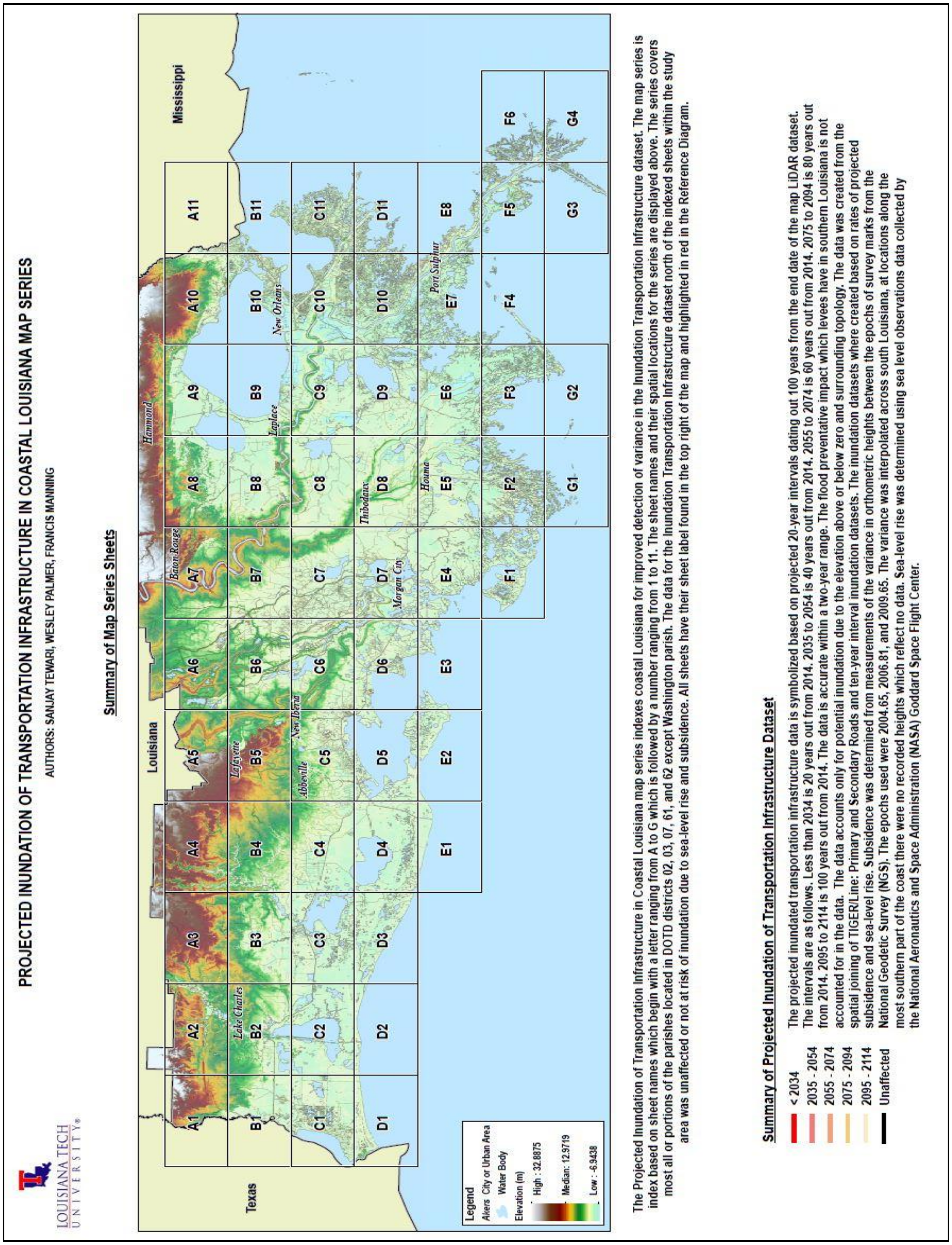

Figure 9. Map book cover page.

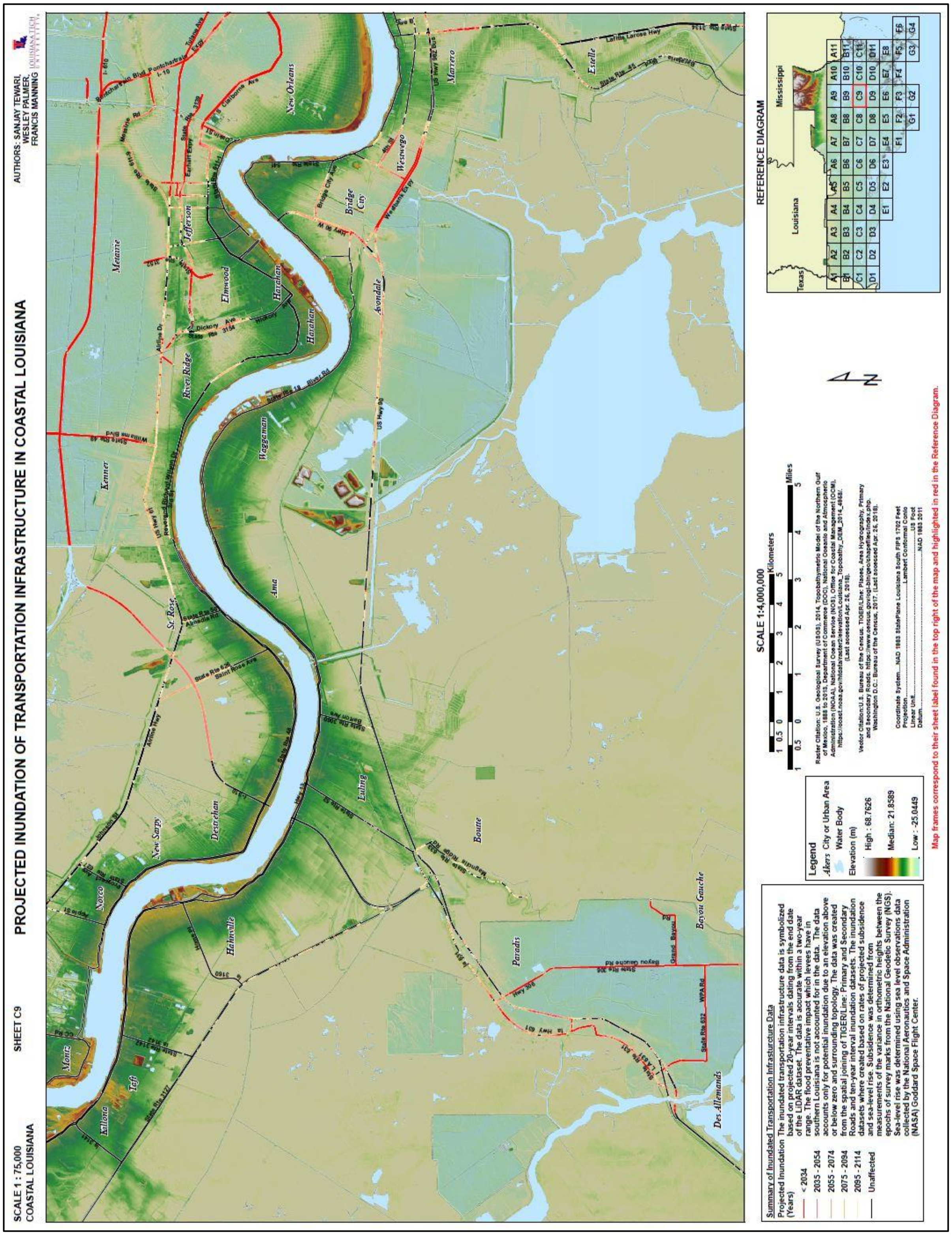

Figure 10. Map sheet C9.

CONCLUSIONS

The results suggest that land subsidence is having a greater impact on transportation infrastructure than sea-level rise. It is projected that by year of 3014, about 2,945 miles or 21% of the existing transportation infrastructure will be impacted because of the combined effect of land subsidence and rising sea level. This estimate does not take account of the effectiveness of extensive levee system present in parts of coastal Louisiana. A significant portion of transportation infrastructure is at risk of getting impacted by the rising sea-water and subsiding land in coastal Louisiana and long term planning would need information that this study provided.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

Add Field: ArcGIS Tool; Adds a new field to a table or the attribute table of a feature class.

Calculate Field: ArcGIS Tool; Calculates the values of a field in an attribute table.

Clip: ArcGIS Tool; Extracts larger input features that overlay the clip features.

CORS: Continuously Operating Reference Station

DEM: Digital Elevation Model

Dissolve: ArcGIS Tool; Aggregates features based on specified attributes.

Epoch: An instant in time chosen as the origin of a survey. The "epoch" then serves as a reference point from which time is measured

Erase: ArcGIS Tool; Creates a feature class by overlaying the input features with the polygons of the erase features. Only those portions of the input features falling outside the erase features outside boundaries are copied to the output feature class.

Extract by Attributes: ArcGIS Tool; Extracts the cells of a raster based on a logical query.

Extract by Mask: ArcGIS Tool; Extracts the cells of a raster that correspond to the areas defined by a mask.

GIS: Geographic Information Systems

GPS: Global Positioning System

IDW: ArcGIS Tool; Interpolates a raster surface from points using an inverse distance weighted (IDW) technique.

Intersect: ArcGIS Tool; Computes a geometric intersection of the input features. Features or portions of features which overlap in all layers and/or feature classes will be written to the output feature class.

LiDAR: Light Detection and Ranging

Merge: ArcGIS Tool; Combines multiple input datasets into a single, new output dataset. This tool can combine point, line, or polygon feature classes or tables.

Minus: ArcGIS Tool; Subtracts the value of the second input raster from the value of the first input raster on a cell-by-cell basis.

ModelBuilder: A visual programming language for building geoprocessing workflows

NASA: National Aeronautics and Space Administration

NGS: National Geodetic Survey

NOAA: National Oceanic and Atmospheric Administration

NSRS: National Spatial Reference System

PID: Identification code for benchmarks starting with two letters followed by four numerical values

Raster Calculator: ArcGIS Tool; Builds and executes a single Map Algebra expression using Python syntax in a calculator-like interface.

Raster to Polygon: ArcGIS Tool; Converts a raster dataset to polygon features.

TBDEM: Topobathymetric Digital Elevation Model

TIGER: Topologically Integrated Geographic Encoding and Referencing

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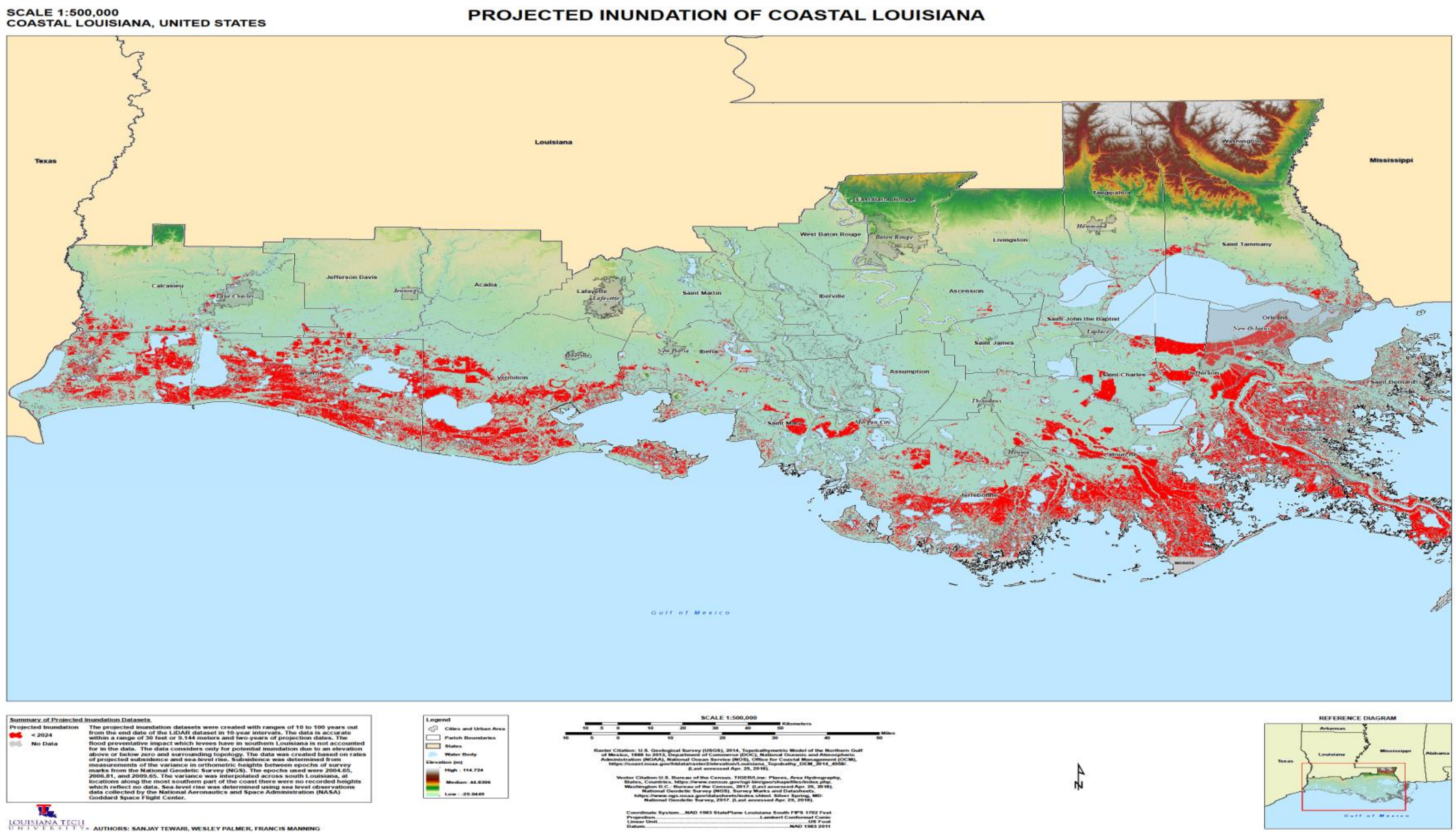
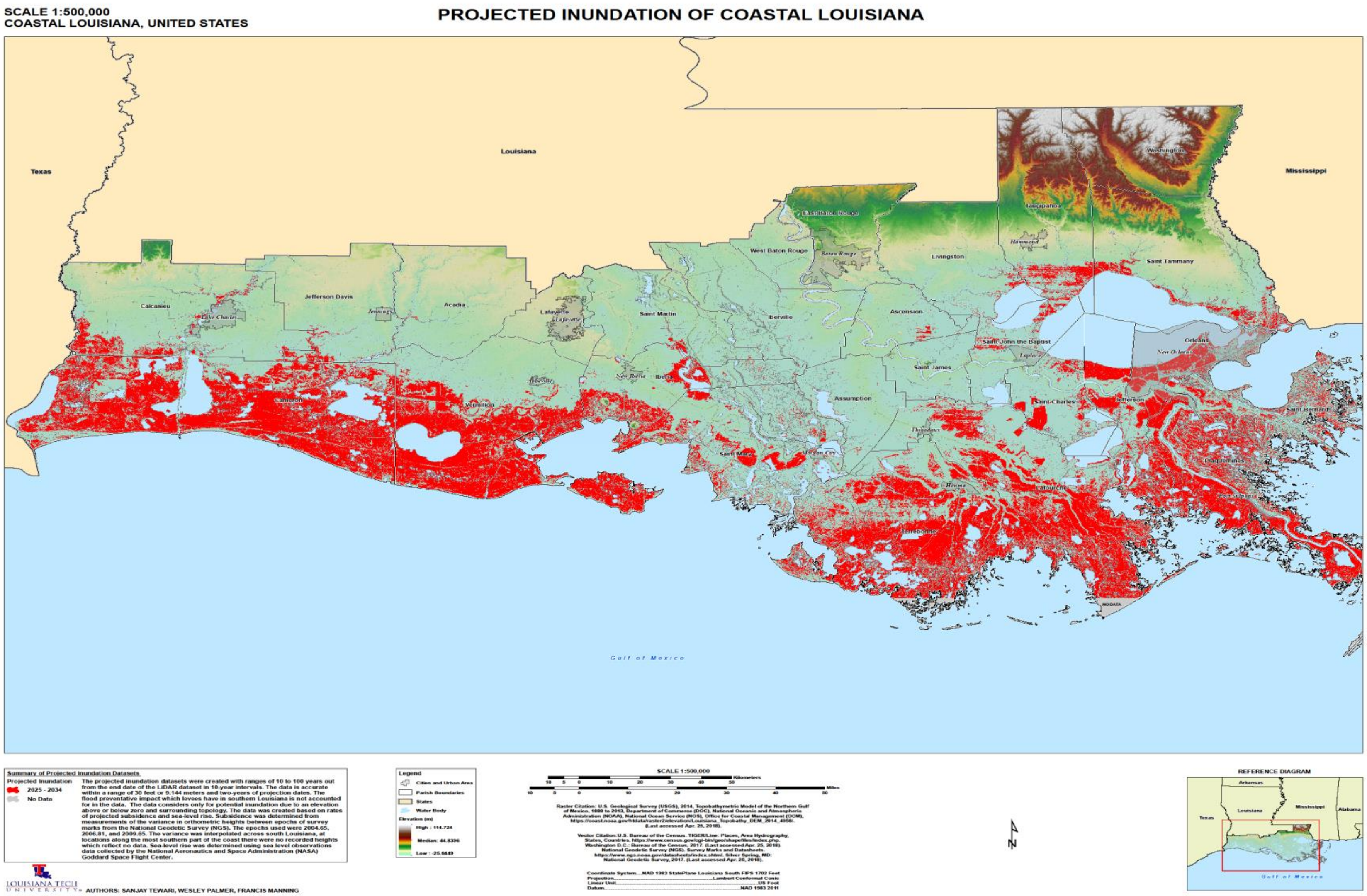
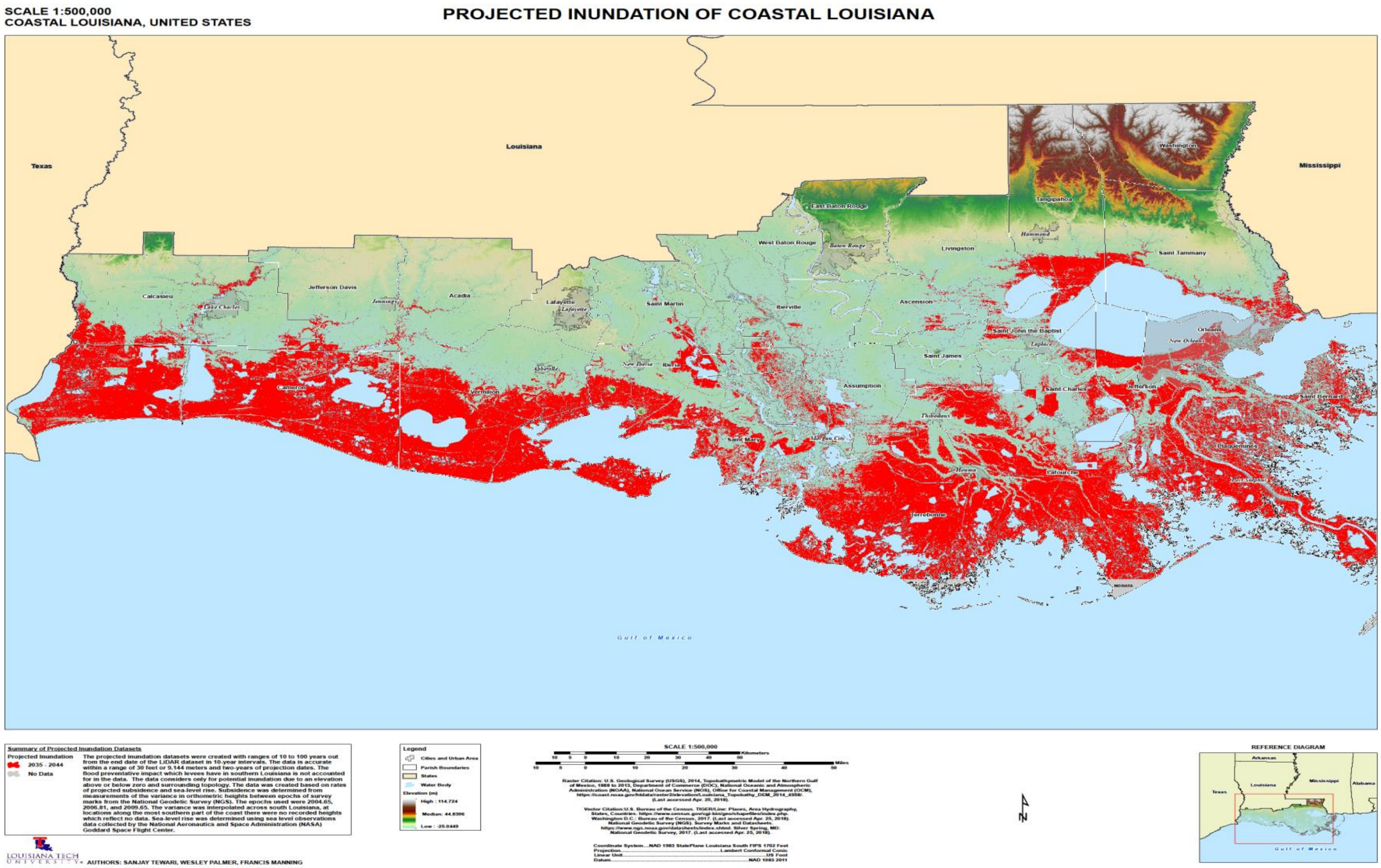
APPENDIX



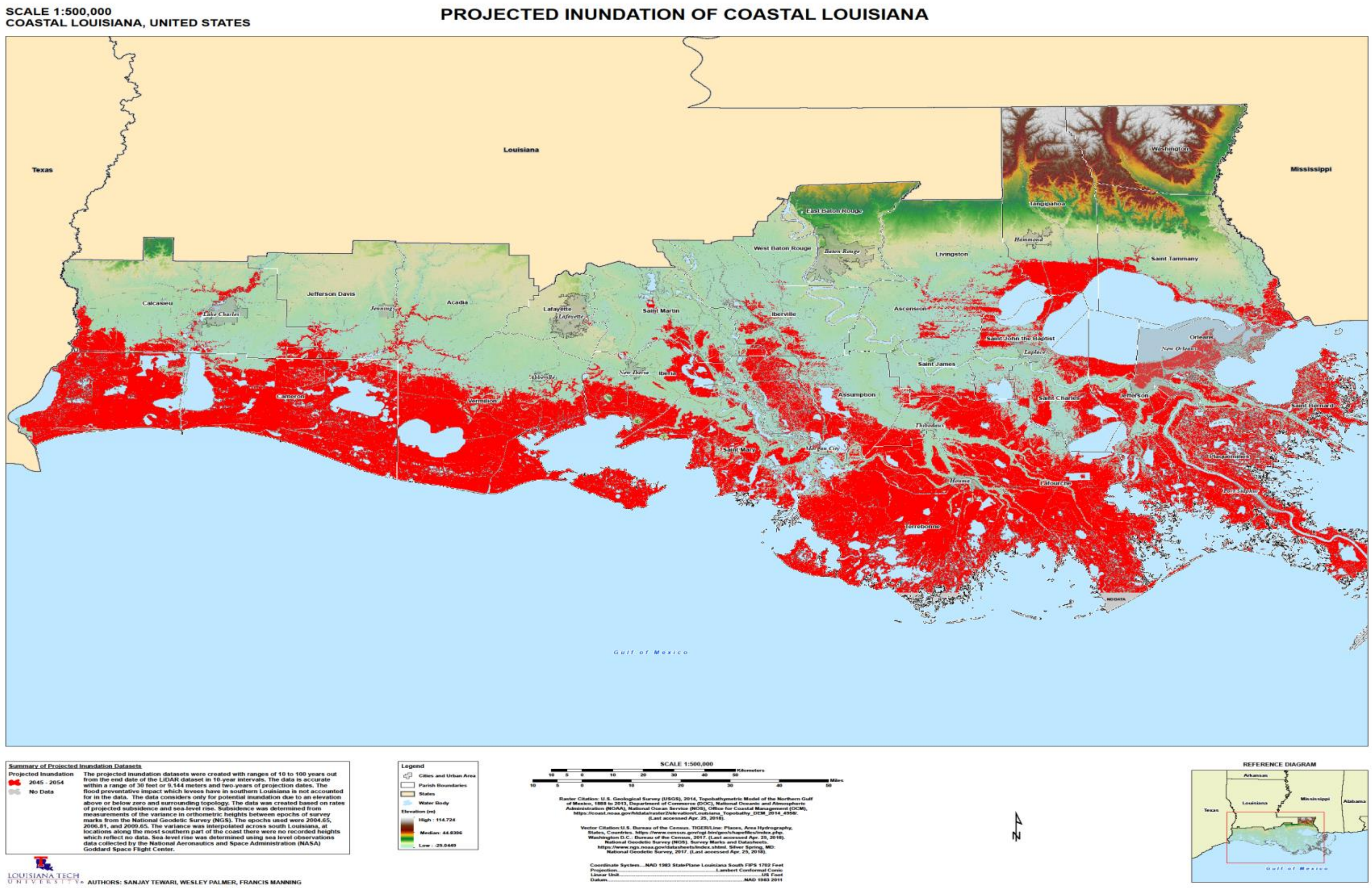
A-1. Projected inundation of coastal Louisiana by 2024.



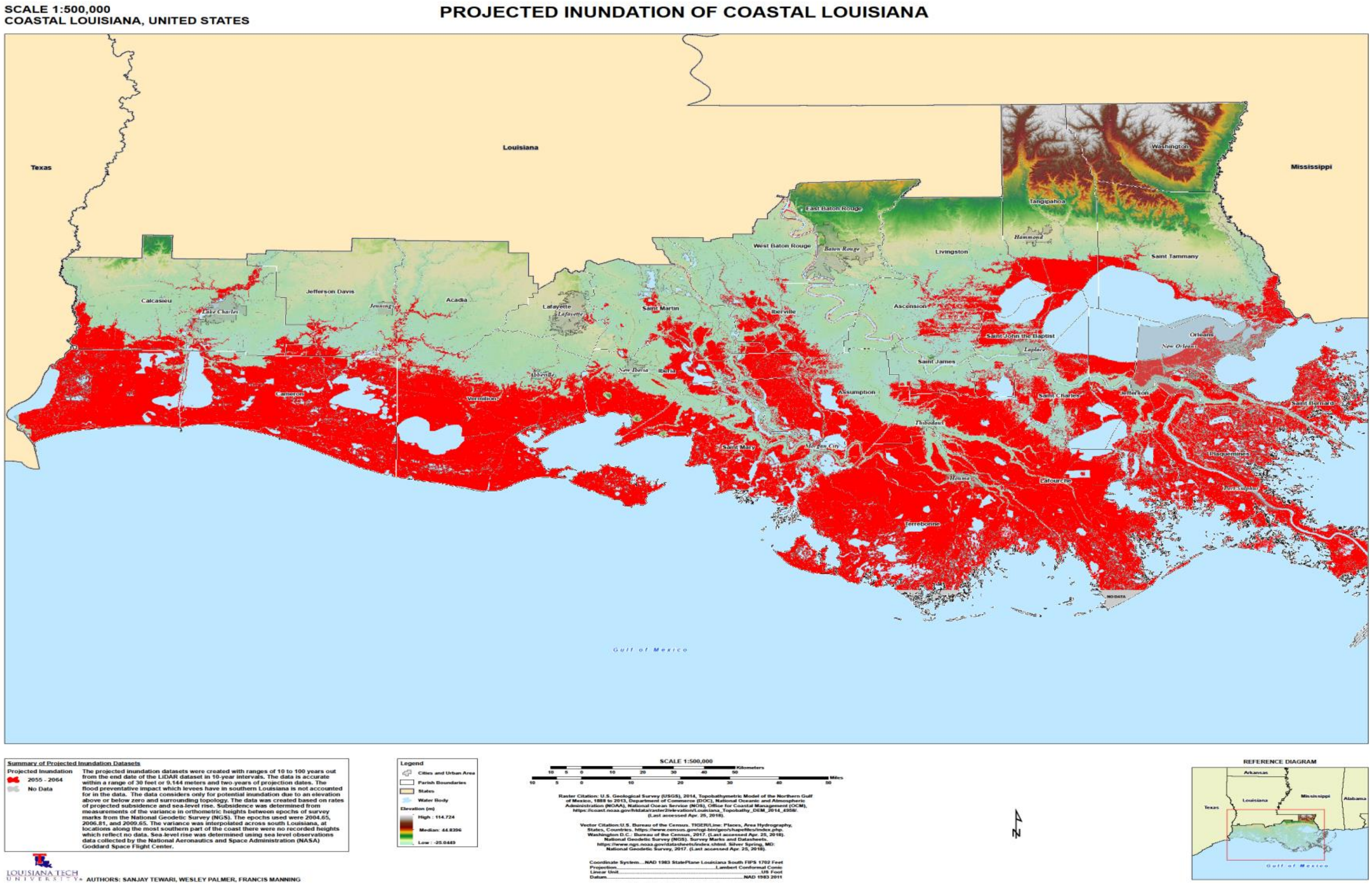
A-2. Projected inundation by 2034.



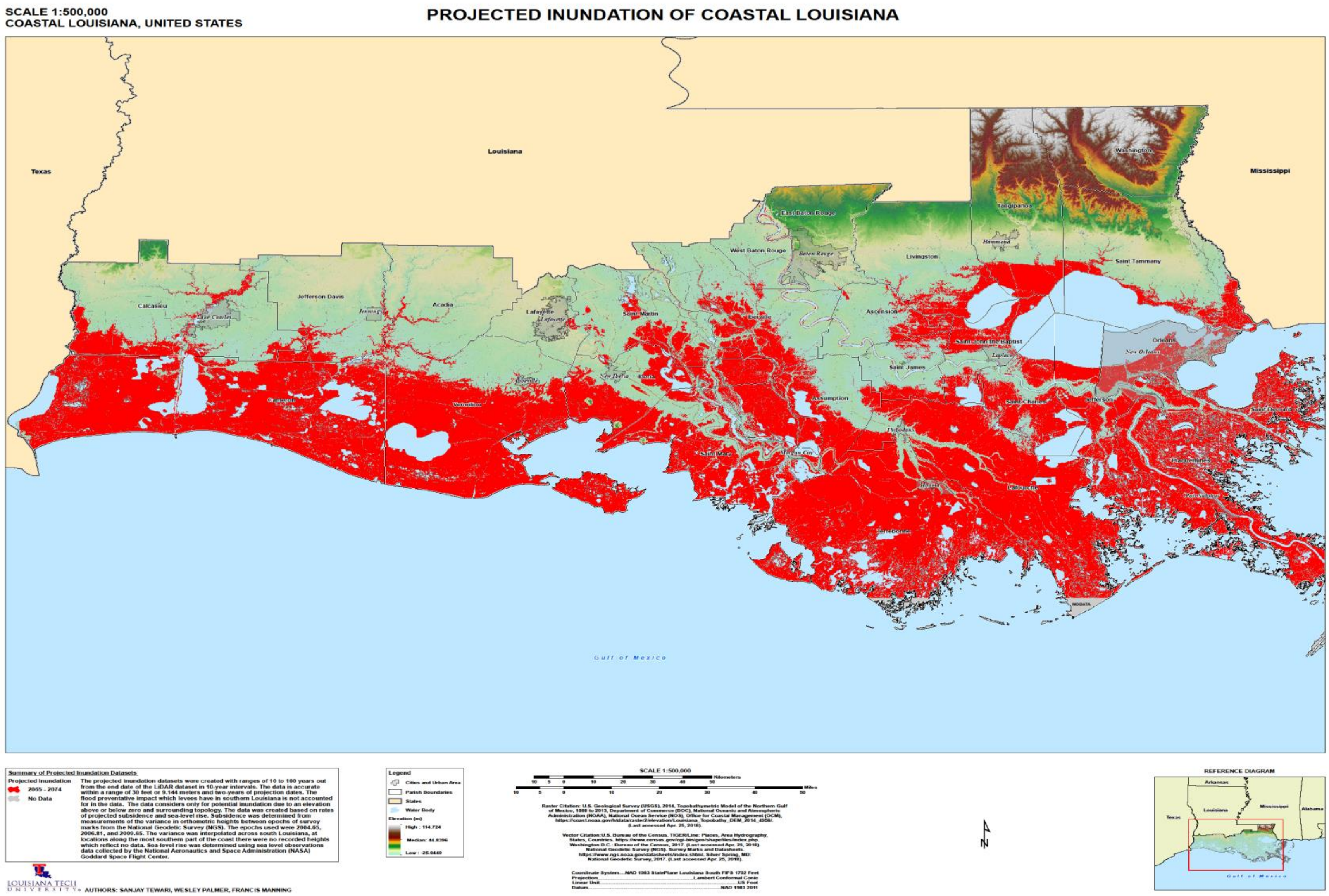
A-3. Projected inundation by 2044.



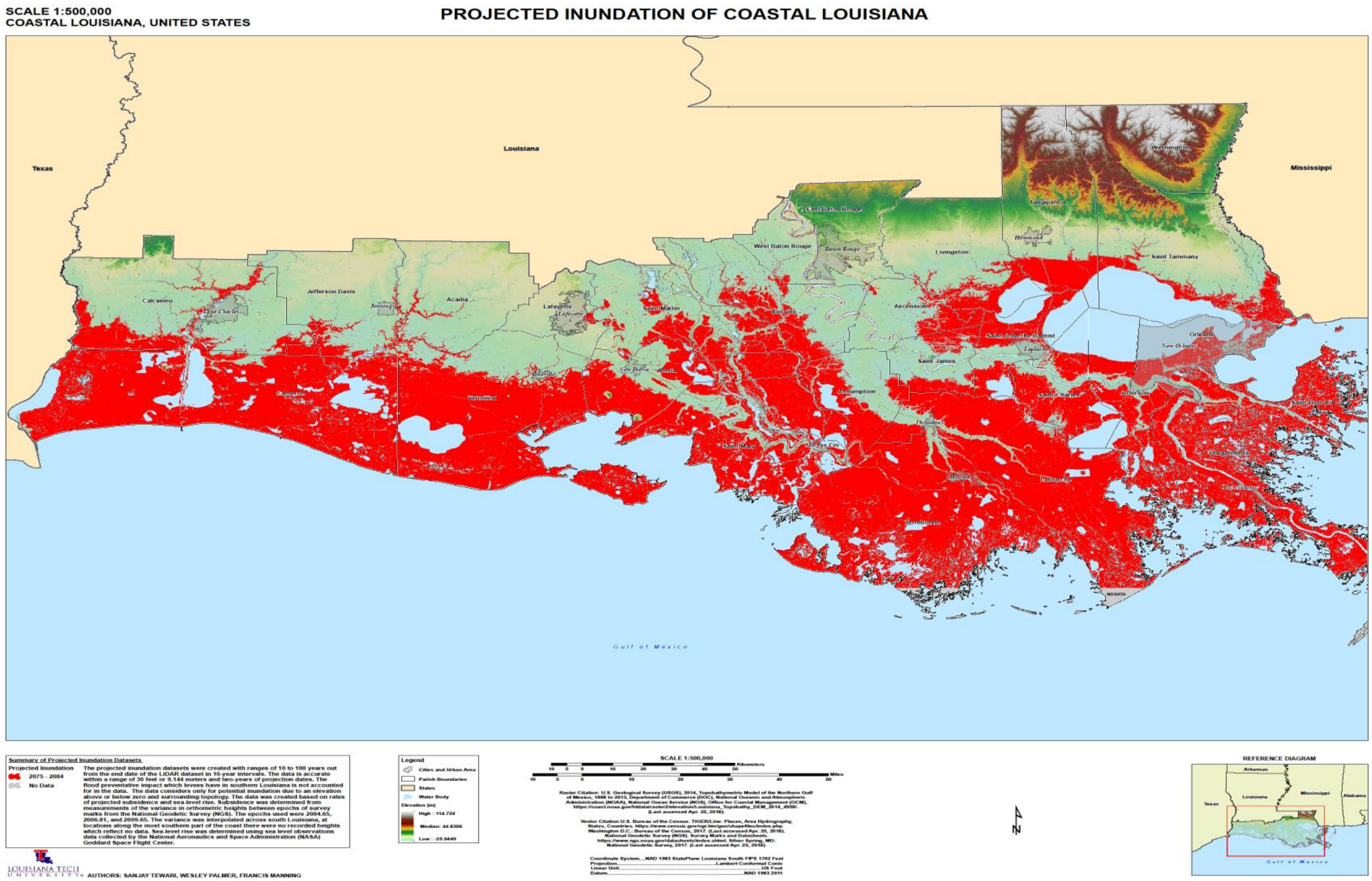
A-4. Projected inundation by 2054.



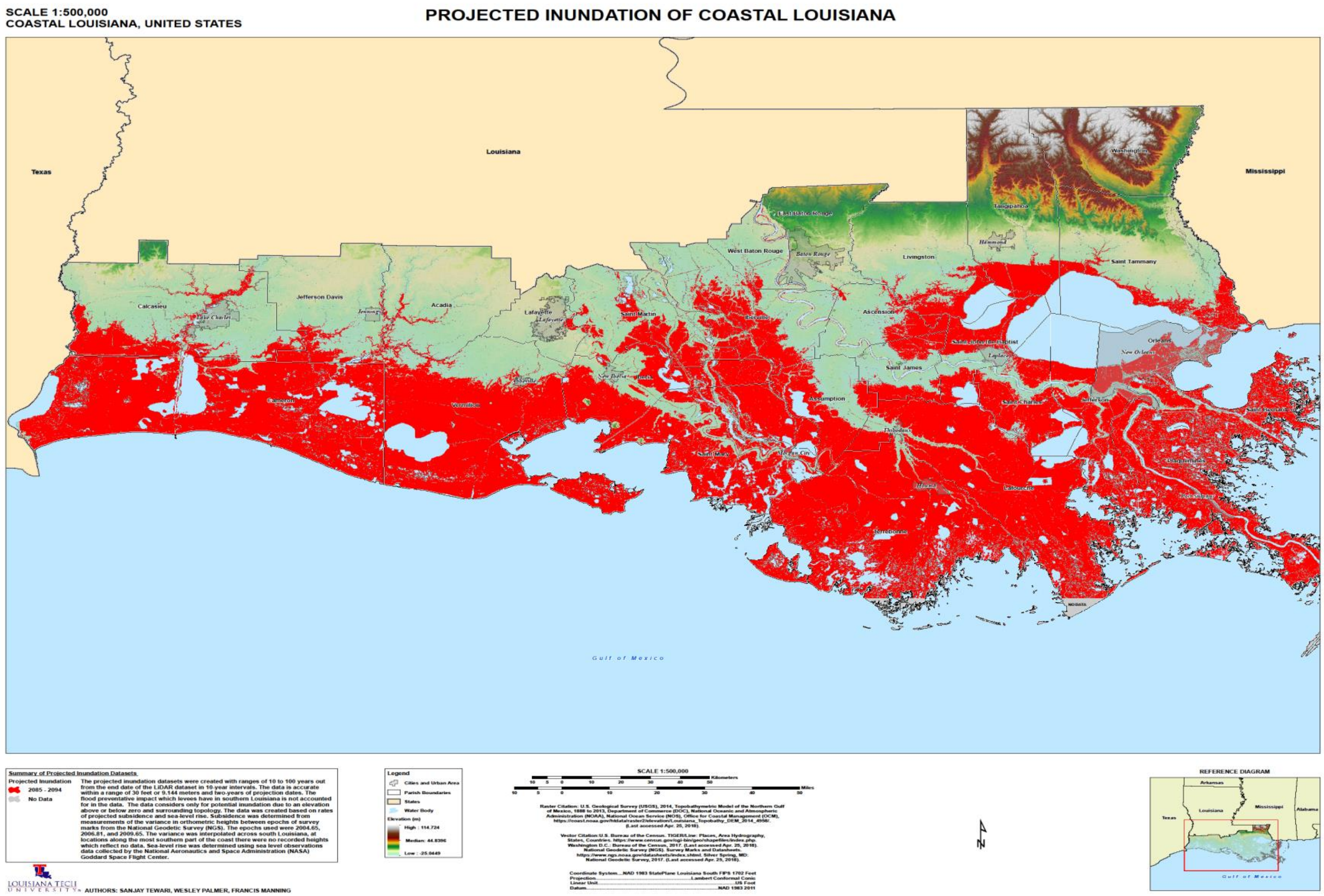
A-5. Projected inundation by 2064.



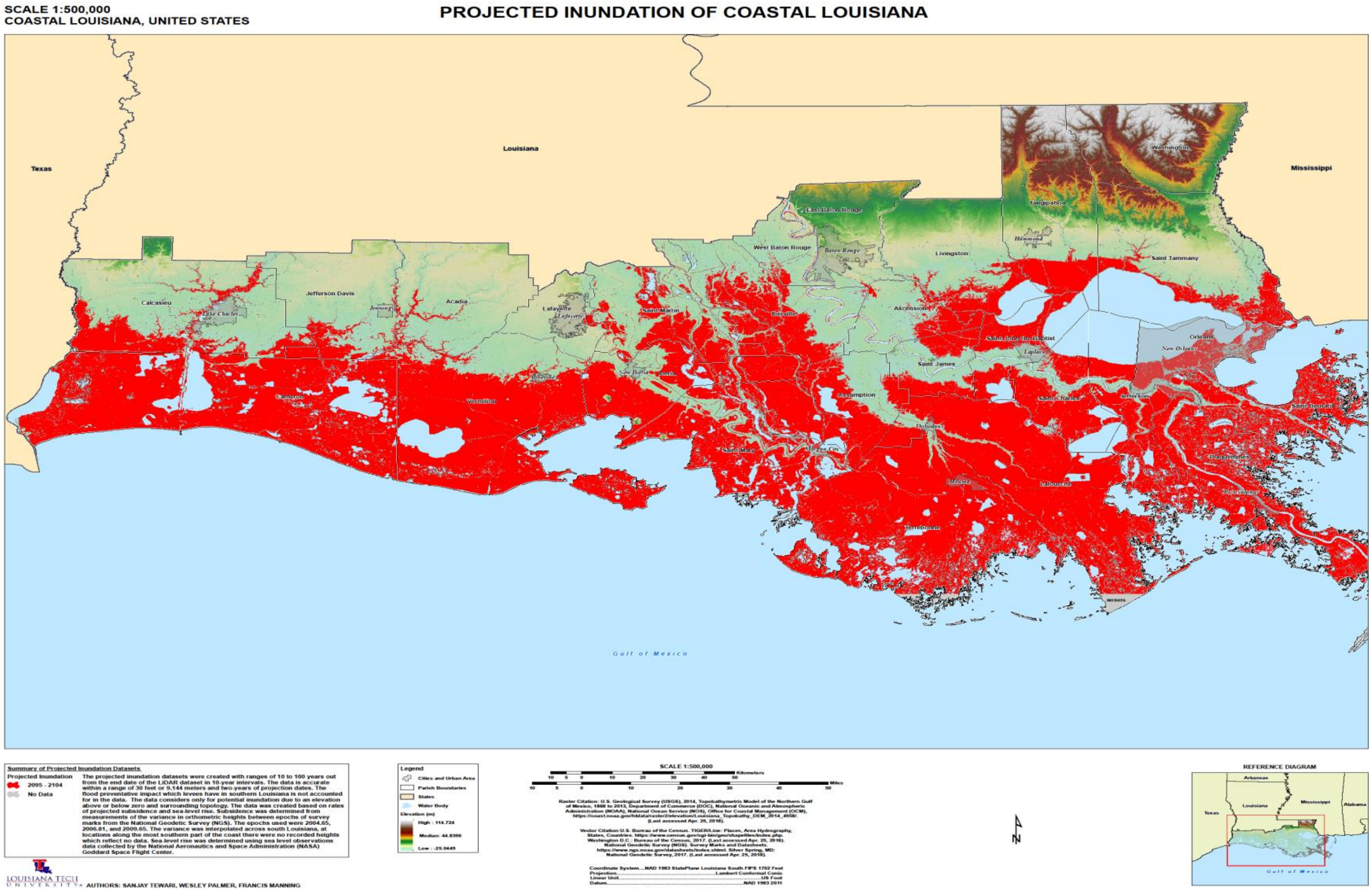
A-6. Projected inundation by 2074.



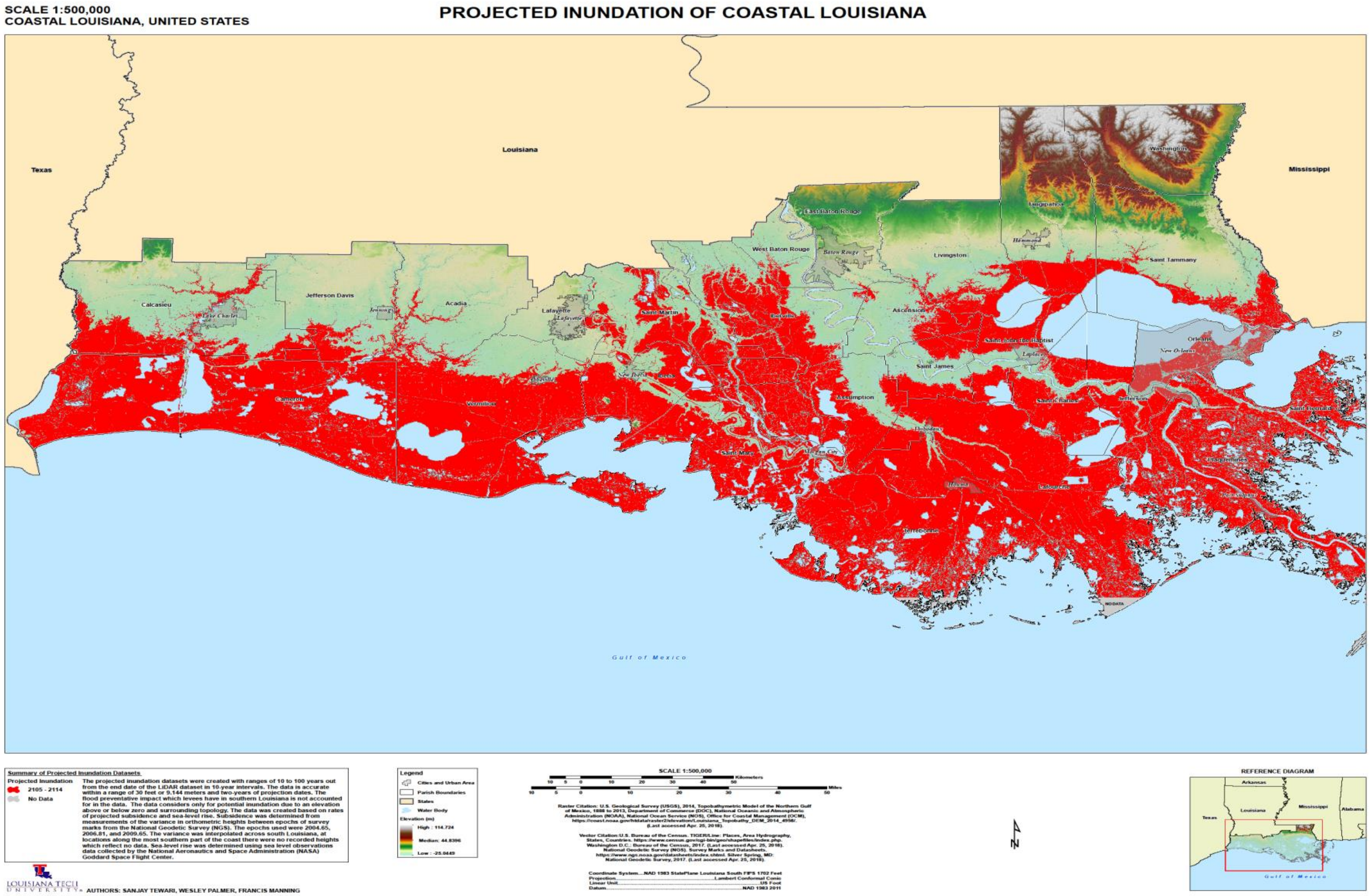
A-7. Projected inundation by 2084.



A-8. Projected inundation by 2094.



A-9. Projected inundation by 3004.



A-10. Projected inundation by 3014.

Please refer to supplement book for additional maps of identified transportation infrastructure potentially at risk because of rising sea level and subsiding land.