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Vulnerability of Fuel Distribution Systems to Hazards in Coastal Communities

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John H. Pardue
Kristen Alevizon
Louisiana State University
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University of Arkansas
4190 Bell Engineering Center
Fayetteville, AR 72701
479-575-6021

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Project Description

Coastal communities are vulnerable to disruptions in their fuel distribution networks due to tropical storms, hurricanes and associated flooding. These disruptions impact communities by limiting fueling in the days following the storm potentially affecting first responders, other critical infrastructure networks and returning residents. After Hurricane Katrina and Hurricane Rita, for example, up to 8% of the nation's refining capacity remained offline for months substantially impacting national fuel supplies (Kumins and Bamberger, 2006). At the local level, flooded fuel stations prevent distribution of fuel supplies even as refining capacity or regional supply is restored.

The fuel distribution network consists of exploration, refining, storage, distribution and transportation elements ultimately ending in the individual fueling stations. Each region has unique supply and distribution characteristics depending on the unequal distribution of refining capacity and pipelines serving regions. Along the Gulf Coast, coastal communities are vulnerable to the elevation and redundancy of the transportation network and the associated fuel station distribution. Even minor flooding can bring a fueling station out of service leading to loss of that capacity to the community until a series of remediation and restoration activities can be completed. While fueling stations can be flood-proofed to some extent, these steps are not consistently required by local, state or federal regulatory structure.

Fueling station capacity consists of above ground (AST) or underground (UST) storage tanks connected to a series of individual pumps and dispensers by supply piping. Flooding impacts including displacement of ASTs and USTs through the action of buoyancy forces on the tanks, leaking from the USTs and ASTs, water or debris entering the USTs or ASTs and electrical damage associated with the USTs, ASTs and dispensing and pump systems. Guidance on preventing flood damage is available including the Petroleum Equipment Institute's (PEI) Recommended Practice 100 and the American Petroleum Institute's (API) Recommended Practice 1615. These standards focus primarily on proper anchoring of USTs to mitigate the impact of buoyancy forces. Despite this guidance, there is no required set of standards for fueling stations built in coastal communities vulnerable to storm surge.

This project had the following objectives, to understand the causes of fuel distribution disruption after coastal hazards and the impact of the coastal community transportation network, to determine the role of fueling station design and environmental regulatory drivers that cause more vulnerability during coastal hazard events and to propose design and mitigation approaches that will result in faster recovery of fuel distribution systems in coastal communities. To address these questions, a network model of the transportation and fuel distribution was built for the Lafourche Parish/Houma, Louisiana system and tested versus the expected level of flooding from storm surge models run at different storm categories. In addition, review of fuel station construction and recovery approaches was conducted to determine whether standards for construction in coastal areas could reduce the frequency of long-term impacts on the fueling network.

Methodological Approach

1. Location

Lafourche Parish is located in southeast Louisiana with a population of 96,318. The parish seat is Thibodeaux and the parish follows Bayou Lafourche, a former interdistributary channel of the Mississippi River. Notably, the parish serves the region and the nation by housing two critical infrastructure elements, the Louisiana Offshore Oil Pipeline (LOOP) and Port Fourchon. The LOOP pipeline crosses into Lafourche Parish at Port Fourchon. It transports crude oil from an offshore offloading facility for oil tankers through the Parish to the Clovelly Hub. The Port, itself, services 90% of the deepwater oil and gas exploration and production in the Gulf of Mexico.

2. MBRA Model and network construction

To determine the impact of fuel network disruption, a network model of roads and the fuel distribution network (fueling stations with above ground and underground storage tanks). The network model consists of 245 links and 102 nodes, where the links represented the road network in Lafourche Parish and the adjacent municipality of Houma, Louisiana (**Figure 1**). Each link represents a road segment and each node represents an intersection between two or more links. Each existing fueling station from the study region (N=146) were identified and placed on the appropriate link. Information from each fueling station included address, fuel dispensing capacity, and presence of UST or AST storage. The road network and associated fuel stations were used to analyze the vulnerability of fuel distribution after a disruption such as a flooding or wind event. The network model was set up within Model-based Risk Analysis (MBRA), a software tool that models critical infrastructure systems as fault trees or networks (Lewis, 2015). For this road and fuel system, MBRA represents this network as a series of nodes and links with different attributes. These networks models are useful for spatially analyzing the road and fuel system, identifying the critical nodes and links and network properties.

3. SLOSH modelling

To assess the vulnerability of the fuel network to storm surge caused flooding, the SLOSH model (Sea, Lake, and Overland Surges from Hurricanes) was used to create flooding scenarios from hurricanes or tropical storms (Jelesnianski, 1992). SLOSH computes a maximum envelope of water for each location by computing the expected level of storm surge using a series of storm tracks. It was selected to provide a range of potential water levels depending on storm intensities. SLOSH models were overlain with the MBRA network model for Lafourche Parish area to identify the fueling stations that would be impacted by water during storm events. SLOSH maps were generated for tropical storms, Category One, Two and Three Hurricanes and a Category 4-5 storm using the Saffir-Simpson scale for storm intensity. Water depths from storm surge maps were overlain with maps generated of the fueling stations and the number of fueling stations impacted by storm surge was computed.

4. Impacts of flooding on fuel stations and recovery costs

Fuel station construction details were reviewed with experts in these systems to determine flooding impacts on below and aboveground storage tanks, pumps and associated secondary containment systems. Based on these discussions and existing industry guidance, recommended flood protection systems were reviewed.

Results and Discussion

<u>Network characteristics</u>

A network was constructed with 245 links, representing roadways, and 102 nodes, representing intersections between the roadway links (**Figure 2**). The network captures two essential features to understand coastal communities in Louisiana: an inland urban center with interlinked road and fuel network and a coastal corridor roadway and fuel network which is oriented normal to the shoreline which lacks the same degree of redundancy in the urban center network. In Louisiana, these coastal corridors follow distributary bayous that are former main Mississippi river channels. Along these waterways, roadways follow both sides of the bayous with bridges that connect either side. The corridor selected for this analysis is the Houma, LA urban area (population in 2013, 34,040) and the lower Lafourche Parish coastal corridor which follows the former Mississippi River channel, Bayou Lafourche. This corridor is significant since it conveys workers to Port Fourchon, an energy port of national significance, and evacuates all communities south of Houma in the case of a hurricane or tropical storm. Since fuel distribution is central to the ability of the transportation network to function, understanding the vulnerability of this network is an important aspect of community resiliency.

The fuel distribution network consists of 146 stations (**Table 1**) averaging 22,775 gallons of gasoline capacity and 13,742 gallons of diesel capacity (from 54 stations), respectively. Of these, 132 stations use underground (USTs) fuel storage tanks (2.77 million gallons of gasoline and 570,077 gallons of diesel) and 14 use above-ground (ASTs) tank storage (261,000 gallons of gasoline and 70,000 gallons of diesel). Stations with ASTs may be more vulnerable to catastrophic flooding impacts because of the challenges of constraining ASTs to large buoyant forces (US EPA, 2010).

Critical links and blocking nodes within the network can be identified using the MBRA network model. In this context, a blocking node or critical link is one that, once removed, the network will no longer function as a unified whole. Critical links and blocking nodes can be identified using several properties. These include the degree of connection which is a measure of how many links connect through each node. Blocking nodes identified by degree are identified for the coastal part of the network (**Figure 3**) and the urban part of the network (**Figure 4**) respectively. The coastal portion of the network tends to have nodes with 1 or 2 links attached (ranked 3 and 4) while the urban network typically has nodes with 3 and 4 links attacked (ranked 1 and 2). If degree of connection was the only measure of the network effectiveness, the nodes that are most interlinked would be most critical. However, if the function of the network is the continued flow of traffic and supply of fuel for workers moving to the coast or evacuees coming from the coast, blocking nodes and critical links may be those that insure flow of traffic and fuel from the urban areas to the coastal zone.

Another network property that may be useful to consider is the "betweenness" of the nodes. Betweenness value of a node is the numbers of paths running through a node to all other nodes in the network (Lewis, 2015). Node with higher betweenness scores are more critical because they serve to link other nodes in the network. An analysis of the network to identify nodes with the greatest betweenness is presented in **Figure 5**. Nodes with the highest values for these measures of connectedness are primarily in the urban portion of the network. These nodes would be critical in maintaining connections between the transportation and fuel distribution networks if events occurred (i.e., flooding) that began to remove links or nodes.

Formal network analysis does not capture important characteristics of the network. For example, the upper urban portion of the network is characterized by higher degree nodes providing more connectivity. In this portion of the network, loss of single links or nodes doesn't readily isolate other links and nodes producing islands. By contrast, the coastal portion of the network is characterized by lower degree nodes with many locations where the entire network could be separated by the loss of a single node or link. An example in the network is LA-1 between Golden Meadow and Leeville where the road is just a few feet above sea level. Flooding of this segment (Link 1-B between Nodes 5 and 100 on the network map) would completely isolate the lower portion of the network. This segment is planned for elevation in a future extension of the LA-1 elevation project, but at present, it remains extremely vulnerable to flooding.

Failure mechanisms for UST and AST Fueling Stations

To analyze the transport and fuel network specifically for flooding, we need to establish the water depths likely to cause damage. Once fueling stations flood, they can be damaged in several ways that prevent reuse of these facilities once waters recede. Stations consist of fuel storage locations, either underground storage tanks (USTs) and above-ground storage tanks (ASTs), connected to electronic fuel dispensers (fuel pumps). Flooding can affect these facilities in several ways including buoyancy, erosion and scour, displacement and loss of product and damage to electrical systems (US EPA, 2010). Buoyancy is the force exerted of flooded USTs and ASTs that can displaced tanks during a flood. The buoyant force is computed as:

$$F_b = 0.134 V_t \gamma FS$$

Where Fb = buoyant force exerted on the tank in pounds, V_t is the volume of the tank in gallons, 0.134 is a conversion factor for gallons to cubic feet, γ is the specific gravity of floodwater (i.e., 62.4 lb/ft^3 for fresh water or 64.1 lb/ft^3 for seawater), and a factor of safety of 1.3.

The net buoyancy for UST's is calculated as:

Net Buoyancy = Tank Buoyancy (F_b) – Tank Weight- the Flood Weight of Soil over the UST

If the net buoyancy is positive, the UST can be displaced out of the ground. Similarly, if an AST is flooded, the net buoyancy is positive and the tank floats since the specific weight of gasoline is 44.9 lb/ft^3. The disparity between the buoyancy and weight increases as the tank increases in size. This creates a challenge in constraining ASTs and USTs from floating if the net buoyancy is large. Oil spills during Hurricane Katrina, for example, resulted from displacement of ASTs at oil storage facilities (Santella et al., 2010).

Erosion and scour from floodwaters can also contribute to fuel station failure by removing soil weight and changing the net buoyant force described above. Once that occurs, the tank is often separated from piping connections to the dispensers resulting in product release. Similar releases can occur when ASTs are floated by these buoyant forces. This release is exacerbated by heavier water entering the tank, displacing the lighter hydrocarbons. Even if the tank is not breaches or displaced, floodwater can enter the tank through the vent system, displacing product and contaminating tank contents. Finally, the floodwaters can damage electronics, both at the dispensers or in the tanks, themselves.

Flood-damaged stations require restoration and remediation activities after flooding events (US EPA, 2010). Integrity testing of the storage tanks is the significant aspect of post-flooding protocols. Louisiana's detailed protocol is reproduced in EPA's Underground Storage Tank Flood Guide (U.S. EPA, 2010). The mechanisms of flooding damage to fuel stations and the detailed protocol. Methods of flood-proofing fueling stations require higher cost construction techniques that are responsive to local ordinances in flood-prone areas. For example, Lafourche Parish passed floodproofing requirements only a few years ago. Industry standards (API, 2011) also describe these methods but it is unclear if and under what circumstances the enhanced floodproofing of underground fuel tanks are practiced in the study area. It is also unknown the frequency of failure of these tanks after these methods are deployed. In the absence of other information, flooding of fueling stations in the study area will render them unusable for fueling during the flood and the time required to accomplish recovery activities (EPA, 2010). A much longer restoration period will be required if UST or AST's driven by buoyancy, break free and spill product. We assume below that every fueling station covered by water will not be able to be used for a significant period of time (days to weeks).

<u>Flooding Projections</u>

After creating the network map for the fuel distribution system, flooding impacts from tropical storms or hurricanes can be assessed using estimates of storm surge intensity associated with storms of different categories. SLOSH maximum envelopes of water were computed as a worst-case scenario when considering forward speed, trajectory and initial tide condition. These estimates were used to assess the relative risk of flooding of the fuel network. Five storm categories were used to assess the risk (Tropical Storm (**Figure 6**), Category 1-3 (**Figure 7-9**) and Category 4/5 (**Figure 10**)). SLOSH predictions were overlain with elevations of each individual station to determine potential for flooding under each storm category.

From a base gasoline capacity of 3.06 million gallons and a base diesel capacity of 672,077, SLOSH tropical storm modelling indicates that none of the fueling stations would be inundated (**Table 2**). As storm intensity increases to a Category One hurricane, 22.5% of gasoline capacity and 22.0% of diesel capacity are inundated. As intensity increases further to a Category Two, the impacts tips and gasoline and diesel capacity are inundated by 92.1% and 92.6%, respectively. Category Three effectively inundated all the capacity with 98.3% and 100% of gasoline and diesel impacted (**Table 2**). A Category Four or Five storm impacted the entire fuel network.

Considering only AST's, none are impacted during tropical storms (**Table 3**). After a Category One storm, ASTs significantly impacted by flooding with 41.4% and 31.4% of gasoline and diesel, respectively. As storm intensity increases to Category Two, 100% of the AST equipped fuel stations are flooded. This more rapid flooding impact is due to the higher frequency of ASTs nearer the coast. In high water table areas, such as areas right near the coast, ASTs are more frequently used to simplify fueling station construction.

To better understand the spatial patterns of fuel network impacts, two parameters, distance from the shoreline (measured from Caminada Headlands shoreline at the furthest point south in Lafourche Parish) and the average elevation of each fueling station. The distribution of fuel capacity with distance from the shoreline shows that fuel supply of both gasoline and diesel is concentrated 30-50 miles inland, in the urban portion of the network (**Table 4**). Another feature is the low fuel capacity between 5-20 miles inland where the population density is the lowest between the coastal communities, in this case, Grand Isle and Port Fourchon, and the inland communities such as Houma.

While the concentration of the fuel network inland suggests that the system would be less impacted by storm surge, the elevation of the stations are all less than 12 feet above sea level (**Table 5**). As a result, once the level of storm surge becomes even at a moderate level (**Table 2**), the entire network becomes impacted. This concentration of the fuel network inland, however, provides some obvious targets for floodproofing so that the network may continue to provide fuel after a flooding event.

<u>Impacts/Benefits of Implementation</u>

The combined fueling station and road network constructed for this project is the first spatial representation of this system for a Louisiana coastal parish. While the Louisiana Governor's Office of Homeland Preparedness (GOHSEP) has a GIS-based system with spatial fueling data that can be used in an emergency, it has not been used for any pre-event analysis function. In March 2017, the PI Pardue presented the network to the state's Supply Chain / Transportation Council. This organization was formed after the catastrophic floods of 2016 to better prepare the state's transportations network, and by extension, other critical infrastructure systems, from failure during these events. The presentation generated discussion among members responsible for understanding the fuel supply during events and follow-up discussions were promised.

<u>Recommendations and Conclusions</u>

A network model of the fuel distribution and transportation network was constructed for Houma, LA and lower Lafourche Parish. The model maps the road network and overlays spatially the 146 gasoline and diesel fueling stations while capturing their capacities and elevation. The network has characteristics of a highly interlinked (higher node degrees) urban sector in the northern part of the network and a less interlinked (lower node degrees) coastal sector. Nodes and links on the model that, once impacted, would divide the network into islands where fuel resupply cannot easily occur.

Flooding impacts on fuel distribution points were reviewed and ranged from water contamination of fuel supplies to catastrophic failure of the storage tanks due to buoyant forces on USTs and ASTs. As a result this review, we conclude that the flooding of fuel distribution points will take these stations off-line from use during the aftermath of the event. Simulated storm surges from storms of different magnitudes demonstrated a tipping point between a Category One and Category Two storm where effectively the entire fuel network would be flooded.

These networks need to be better understood to increase the resilience of coastal communities. Recommendations include:

1. Network analysis tools need to be developed to identify vulnerability for these systems with low node degree connections

2. Methods for floodproofing fuel networks need to be developed that move beyond UST anchoring and other construction techniques.

3. Overlaying this information with functional transportation models describing the flow of vehicles with actual fuel needs may identify vulnerable segments of the network not apparent in the simpler network modelling approaches utilized above.

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Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
3090	Conoco (Kajun Truck Plaza)	Golden Meadow	AST	20,000.00	10,000.00	5	2.61
				20,000.00	10,000.00		
182-H	Civic Express	Houma	UST	32,000.00	8,000.00	6	38
182-H	Barrow Street Chevron	Houma	UST	12,000.00	-	8	38.2
				44,000.00	8,000.00		
182-I	Exxon	Houma	UST	18,000.00	3,000.00	9	20
				18,000.00	3,000.00		
182-K	Long's Country Market	Gibson	UST	8,000.00	-	4	33.5
182-K	Gibson Food Mart	Gibson	UST	18,000.00	6,000.00	7	36
				26,000.00	6,000.00		
182-N	Danos Exxon Service Station	Houma	UST	18,000.00	3,000.00	10	37.2
				18,000.00	3,000.00		
182-O	Main Conoco	Houma	UST	20,000.00	-	6	39.4
				20,000.00	-		
1-A	Bridgeside Marina	Grand Isle	AST	14,000.00	4,000.00	4	1.54
1-A	Conoco (Jo-Bob's Gas and Grill)	Grand Isle	AST	20,000.00	6,000.00	5	1.1
1-A	Shell	Grand Isle	AST	20,000.00	6,000.00	6	1.1
				54,000.00	16,000.00		

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
1-C	Tom's Service Station	Golden Meadow	UST	16,000.00	-	1	23
				16,000.00	-		
1-E	Jack's Exxon Service Inc	Cut Off	UST	18,000.00	-	3	32.6
1-E	A&J Discount	Cut off	UST	16,000.00	8,000.00	4	33.6
1-E	Crab Station LLC	Larose	UST	20,000.00	-	5	35.7
1-E	Gaubert Food Mart #21	Larose	UST	16,000.00	8,000.00	5	35.7
				70,000.00	16,000.00		
1-F	Go-Bear's Food Marts Inc #22	Larose	UST	24,000.00	-	3	36
1-F	Texaco (Gaubert Food Mart # 14)	Lockport	UST	20,000.00	-	2	39.6
1-F	Lockport Discount	Lockport	UST	14,000.00	-	3	39.2
1-F	Mobile (Lockport Self Serve)	Lockport	UST	20,000.00	-	4	39.7
1-F	Conoco (Bayou Quick Stop)	Lockport	UST	12,000.00	-	5	39.2
1-F	Carol's Shell Service Station	Lockport	UST	16,000.00	8,000.00	5	39.4
1-F	Lockport Exxon	Lockport	UST	8,000.00	-	6	39.3
1-F	Murphy USA #7415	Raceland	UST	40,000.00	20,000.00	9	42.4
1-F	Jacob Naquin Enterprises	Raceland	UST	20,000.00	10,000.00	9	43
1-F	Cash Magic Raceland	Raceland	UST	28,000.00	14,000.00	9	43
1-F	Tobacco Plus #23	Mathews	UST	30,000.00	-	10	42
1-F	Shell (Jester's Court)	Raceland	UST	20,000.00	-	10	43.1
				252,000.00	52,000.00		
1-G	EZ Serve (Hiram Properties Inc)	Raceland	UST	20,000.00	-	10	44.7
1-G	Shop Rite Food Store #33	Raceland	UST	24,000.00	-	10	44.9
				44,000.00	-		

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
24-C	Mobil	Gray	UST	20,000.00	-	4	43.9
				20,000.00	-		
24-F	Shell (Gotta Stop)	Bourg	UST	18,000.00	3,000.00	5	32.6
				18,000.00	3,000.00		
24-G	Conoco (J&N Truck Stop Inc)	Houma	UST	16,000.00	16,000.00	9	37.1
				16,000.00	16,000.00		
24-N	Shamson Inc	Houma	UST	18,000.00	-	8	41.6
24-N	Cheap Smokes #10 Inc	Houma	UST	16,000.00	-	9	41.8
				34,000.00	-		
24-O	Gray Food Mart LLC	Gray	UST	18,000.00	-	11	43.4
24-O	Shell (Terrebonne Truck Stop)	Gray	UST	22,000.00	14,000.00	12	43.6
				40,000.00	14,000.00		
24-P	Chevron (Shop Rite #36)	Bourg	UST	20,000.00	-	8	35.3
				20,000.00	-		
24-Q	Time Stop	Houma	UST	30,000.00	-	7	38.8
24-Q	24/7 Discount	Houma	UST	12,000.00	3,000.00	8	38.9
				42,000.00	3,000.00		
24-R	Dashley's	Houma	UST	12,000.00	-	4	40.8
24-R	BJ's Country Corner #2	Houma	UST	9,000.00	-	8	40.4

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
24-R	Texaco Houma	Houma	UST	30,000.00	10,000.00	8	40.6
24-R	Donald's Service Station	Houma	UST	22,000.00	3,000.00	9	40.1
24-R	Broadmoor Full Services	Houma	UST	20,000.00	-	8	41.2
24-R	Southland Shell	Houma	UST	30,000.00	10,000.00	8	41.2
24-R	Shop Rite #29/ Tobacco Plus	Houma	UST	16,000.00	-	9	41.2
				139,000.00	23,000.00		
3040-B	Tunnel Express	Houma	UST	14,000.00	6,000.00	8	37.6
				14,000.00	6,000.00		
3040-D	Valero	Houma	UST	24,000.00	12,000.00	5	39
				24,000.00	12,000.00		
3040-F	Tuneel Self Serve	Houma	UST	24,000.00	-	7	38.6
				72,000.00	24,000.00		
3040-I	Murphy Oil USA inc- Murphy Express #8535	Houma	UST	40,000.00	20,000.00	1	40.9
3040-I	Chevron	Houma	UST	22,000.00	6,000.00	4	39.8
3040-I	Mobil (DPB #2)	Houma	UST	20,000.00	6,000.00	4	39.9
				82,000.00	32,000.00		
3040-J	Super Serve #4	Houma	UST	30,000.00	-	4	39.7
				30,000.00			

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
306-B	CS Ventures Inc dba Jim's	Des Allemands	UST	14,000.00	8,000.00	0	52.3
				14,000.00	8,000.00		
3087-C	Convenience King II	Houma	UST	24,000.00	-	5	37.7
3087-C	On the Go	Houma	UST	10,000.00	10,000.00	7	37.8
				34,000.00	10,000.00		
308-A	Jordan's Mini Store LLC	Galliano	UST	8,000.00	-	3	25.8
308-A	Renovations Inc	Cut Off	UST	15,000.00	-	3	28.8
308-A	Shell	Cut Off	AST	22,000.00	-	3	34.6
				45,000.00	-		
308-B	Cash Magic Larose LLC	Larose	UST	-	14,000.00	4	36.5
308-B	Shell (Breaux & Duplantis enterprise LLC- Jester's Court II Truck Stop & Casino)	Mathews	UST	30,000.00	15,000.00	6	42
				30,000.00	29,000.00		
308-C	Marvin's Texaco & Wrecking Yrd	Raceland	UST	14,000.00	2,000.00	9	44.7
308-C	Shop & Gas LLC- Shop & Gas convenient store	Raceland	UST	24,000.00	-	10	44.6
				38,000.00	2,000.00		
311-B	Rebecca Truck Plaza & Casino LLC	Schriever	UST	22,000.00	14,000.00	11	44.5
				22,000.00	14,000.00		
311-C	Shell (Visco Resources LLC- X-Stop)	Houma	UST	24,000.00	12,000.00	8	39.1
311-C	Plantation Truck Plaa & Casino	Houma	UST	28,000.00	14,000.00	9	38.3
				52,000.00	26,000.00		

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
315-B	Tommy's Stop & Go	Theriot	UST	24,000.00	2,000.00	5	25.4
315-B	Exxon	Houma	AST	55,000.00	-	5	33.5
				79,000.00	2,000.00		
316-B	Exxon (Big Wheels Travel Center LLC)	Gray	UST	25,000.00	12,000.00	9	44.6
316-B	BJ's #3	Houma	UST	20,000.00	-	10	44.1
316-B	BJ's Country Corner	Gray	UST	16,000.00	4,000.00	11	44.2
				61,000.00	16,000.00		
3235-A	Boudreaux's Landing	Golden Meadow	UST	32,000.00	8,000.00	0	22.3
3235-A	Shell T-Pops Mart (SFTP LLC –Jester's Court)	Golden Meadow	UST	24,000.00	4,000.00	0	22.4
3235-A	Chevron	Galliano	UST	30,000.00	10,000.00	0	24.5
3235-A	Chevron Galliano	Galliano	UST	-	12,000.00	0	28.8
				86,000.00	34,000.00		
3235-B	First Cast LLC	Cut Off	UST	20,000.00	-	2	29.5
				20,000.00	-		
55-A	Montegut Mini-Mart	Montegut	AST	14,000.00	8,000.00	4	26.8
				14,000.00	8,000.00		
56-B	Bayou Dock Shop	Chauvin	AST	8,000.00	6,000.00	5	21.6
56-B	Clearview Mini Mart	Chauvin	UST	12,000.00	-	6	27
				20,000.00	6,000.00		

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
57-D	Sarah's	Houma	UST	16,000.00	10,000.00	4	29
57-D	Ashland Mini Mart Inc	Houma	UST	22,000.00	-	7	31.5
57-D	Exxon	Houma	UST	32,000.00	-	7	35
57-D	Chevron Jubilee	Houma	UST	20,000.00	6,000.00	8	35
57-D	Smoke N Go LLC	Houma	UST	30,000.00	10,000.00	8	36.1
57-D	H&M Shell	Houma	UST	32,000.00	-	8	36.4
57-D	Cash Magic (CITGO)	Houma	UST	28,000.00	14,000.00	10	36.4
				180,000.00	40,000.00		
57-G	Murphy Oil USA #6832	Houma	UST	40,000.00	-	7	37
57-G	Nocko's	Houma	UST	16,000.00	-	8	36.9
57-G	Los Primos	Houma	UST	16,000.00	4,000.00	9	36.9
57-G	Shop Rite #27	Houma	UST	22,000.00	-	9	37
57-G	S&T Food Mart	Houma	UST	18,000.00	-	9	37.4
				112,000.00	4,000.00		
58-A	Tee Lee's Mini-Mart	Montegut	UST	12,000.00	6,000.00	4	27.7
				12,000.00	6,000.00		
661-B	Quickie Stop	Houma	UST	12,000.00	-	6	37.6
				12,000.00	-		
661-C	Texaco (Gaubert Oil Co Inc)	Houma	UST	22,000.00	10,000.00	6	37
661-C	Chevron (Shop Rite #12)	Houma	UST	22,000.00		8	37.3
				44,000.00	10,000.00		

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
665-A	Cajun Corner Stop	Montegut	UST	18,000.00	6,000.00	4	30.5
				18,000.00	6,000.00		
90-A	Cy's Landing	Des Allemands	UST	6,000.00	4,000.00	3	52.9
90-A	Valero (Bayou Travel Center)	Des Allemands	UST	16,000.00	20,000.00	4	53
				22,000.00	24,000.00		
90-F	Wilson's Kountry Korner& Deli Inc	Schriever	UST	20,000.00	8,000.00	4	40.6
				20,000.00	8,000.00		
90-H	Shell (Presto Fuel Center)	Raceland	UST	20,000.00	12,000.00	3	46.5
				20,000.00	12,000.00		
90-L	Texaco Paradis	Paradis	UST	26,000.00	-	0	57.4
90-L	Shell (Big River Food & Fuel)	Paradis	UST	36,000.00	12,000.00	1	57.1
90-L	Valero (Birdies Food& Fuel #15)	Paradis	UST	22,000.00	-	2	57.2
90-L	Shell (The Outdoor Express)	Boutte	UST	20,000.00	-	3	58
90-L	Race Trac	Boutte	UST	36,000.00	-	4	58.2
90-L	Exxon	Boutte	UST	34,000.00	6,000.00	4	58.2
				174,000.00	18,000.00		
90-M	Shell (Jester's Court Bouttee)	Boutte	UST	30,000.00	-	3	58.8
				30,000.00			
Bayou Gardens	Express Convenience Centers LLC	Houma	UST	20,000.00	-	4	41.8

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
Bayou Gardens	Wag-A-Pak	Houma	UST	18,000.00	-	5	41.7
				38,000.00	-		
Node 2	Conoco (Equilon Pipeline Co LLC)	Golden Meadow	AST	20,000.00	5,000.00	6	6.85
Node 21	Raceland Exxon Convenience	Raceland	UST	18,000.00	6,000.00	12	44.5
Node 22	Lucky Mart	Gray	UST	16,000.00	-	8	45.4
				16,000.00			
Node 36	Cecil Lapeyrouse Grocery	Chauvin	AST	11,000.00	3,000.00	2	17.7
				11,000.00	3,000.00		
Node 43	Exxon	Bourg	UST	24,000.00	-	4	32.1
				24,000.00			
Node 46	Cajun Magic Truck Stop	Houma	UST	24,000.00	20,000.00	8	35.3
				24,000.00	20,000.00		
Node 53	Bayou Express	Houma	UST	24,000.00	-	6	38
				24,000.00			

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
Node 60	Shell (Bryson Discount)	Houma	UST	18,000.00	4,000.00	0	38.6
Node 60	Bryson Discount (Shell)	Houma	UST	20,000.00	-	0	38.6
				38,000.00	4,000.00		
Node 61	Sarah's Discount	Houma	UST	22,000.00	-	0	38.9
				22,000.00			
Node 64	Shop-N-Bag Corp	Houma	UST	14,000.00	-	7	38.8
				14,000.00			
Node 65	Jubilee	Houma	AST	9,000.00	9,000.00	9	37.8
				9,000.00	9,000.00		
Node 7	Galliano Truck Plaza & Casino LLP	Cut Off	UST	10,000.00	14,000.00	0	28.8
Node 7	Texaco Galliano	Galliano	UST	22,000.00	10,000.00	0	28.9
Node 7	Murphy USA #7558	Galliano	UST	40,000.00	20,000.00	0	29
				72,000.00	44,000.00		
Node 71	Chevron	Houma	UST	26,000.00	2,000.00	9	39.9
				26,000.00	2,000.00		
Node 72	Shell	Houma	UST	6,000.00	6,000.00	6	38.8
				6,000.00	6,000.00		
Node 73	Sam's Club Store #6521	Houma	UST	60,000.00	-	6	41.5
				60,000.00			

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
Node 74	Chevron Houma	Houma	UST	30,000.00	-	11	41.5
				30,000.00			
Node 75	Mobil (Price's Big star Supermarket Inc)	Montegut	UST	4,000.00	-	5	27.7
				4,000.00			
Node 76	Road Runner Discount	Houma	UST	24,000.00	-	5	38.4
				24,000.00			
Node 77	Chevron	Houma	UST	30,000.00	-	9	43
				30,000.00			
Node 78	Houma Coteau Travel Plaza (Texaco Houma)	Houma	UST	16,000.00	4,000.00	5	40.6
				16,000.00	4,000.00		
Node 79	Valero Corner Store #375	Houma	UST	27,217.00	10,077.00	7	41.4
Node 79	Chevron	Houma	UST	20,000.00	10,000.00	7	41.4
Node 79	B&B Mart and Fuel	Houma	UST	34,000.00	-	8	41.5
				81,217.00	20,077.00		
Node 8	Tobacco Plus #15	Cut Off	UST	27,000.00	10,000.00	3	29.2
				27,000.00	10,000.00		
Node 85	Hill City Oil Co Inc. Marty J's Truck Stop and Casino	Chauvin	AST	20,000.00	5,000.00	4	27.7
				20,000.00	5,000.00		

Table 1. Fuel station in network (Houma, LA and lower Lafourche Parish) (cont.)

Link	Fuel Station	Town/City	tank type	gasoline (gallons)	diesel (Gallons)	elevation (ft)	distance from coast (mi)
Node 89	Chevron (Siarc Inc)	Des Allemands	UST	16,000.00	10,000.00	2	53.7
				16,000.00	10,000.00		
Node 97	Quick Zone Inc	Houma	UST	28,000.00	-	9	39.4
				28,000.00			
Node 98	Exxon Park Avenue	Houma	UST	30,000.00	-	6	39.5
Node 98	Chevron	Houma	UST	24,000.00	-	10	39.2
				54,000.00			
old 1-B	Griffin's Station Marina Inc	Leeville	AST	14,000.00	4,000.00	3	12.1
old 1-B	Tyd's Bait and Tackle	Golden Meadow	AST	14,000.00	4,000.00	3	12.3
				28,000.00	8,000.00		
St.Charles	Shop Rite #46	Houma	UST	20,000.00	10,000.00	6	38
St.Charles	St. Charles Shell	Houma	UST	20,000.00	-	6	38.1
				40,000.00	10,000.00		
Network Sum	UST capacity (gallons)			2.77E+06	5.70E+05		
	AST capacity (gallons)			2.61E+05	7.00E+04		

Table 2. Flooding impacts on base gasoline and diesel capacity in the lower Lafourche Parish, Houma, Louisiana network

Storm Category	Gasoline Capacity (gallons)	Diesel Capacity (gallons)	% Gasoline Impacted	% Diesel Impacted
Tropical	3,064,217	672,077	0	0
Cat 1	2,374,217	524,077	22.5	22.0
Cat 2	242,000	50,000	92.1	92.6
Cat 3	52,000	0	98.3	100
Cat 4/5	0	0	100	100

Table 3. Flooding impacts on AST storage in the lower Lafourche Parish, Houma, Louisiana network

Storm Category	Gasoline Capacity (gallons)	Diesel Capacity (gallons)	% Gasoline Impacted	% Diesel Impacted
Tropical	261,000	70,000	0	0
Cat 1	153,000	48,000	41.4	31.4
Cat 2	0	0	100	100
Cat 3	0	0	100	100
Cat 4/5	0	0	100	100

Table 4. Distance from shoreline for base gasoline and diesel capacity in the lower Lafourche Parish, Houma, Louisiana network

Distance from Shoreline (mi)	Gasoline Capacity (gallons)	Diesel Capacity (gallons)
0-1	0	0
1-5	74,000	26,000
5-10	48,000	13,000
10-20	29,000	6,000
20-30	354,000	125,000
30-40	1,368,000	244,000
40-50	935,217	198,077
50-60	256,000	60,000

Table 5. Elevation of base gasoline and diesel capacity in the lower Lafourche Parish, Houma, Louisiana network

Elevation (ft)	Gasoline Capacity (gallons)	Diesel Capacity (gallons)
0-3	671,000	169,000
4-6	1,071,000	226,000
7-9	988,217	222,077
10-12	334,000	55,000

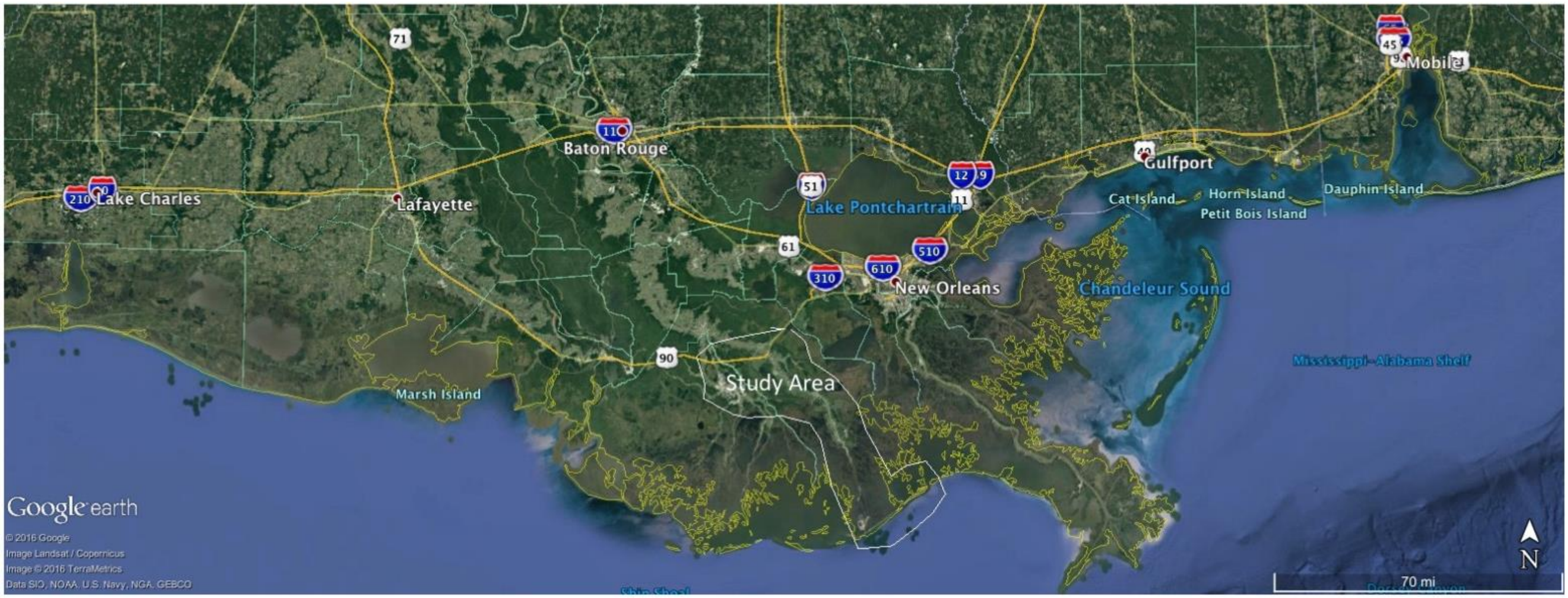

Figure 1. Study area for fuel/transport network.

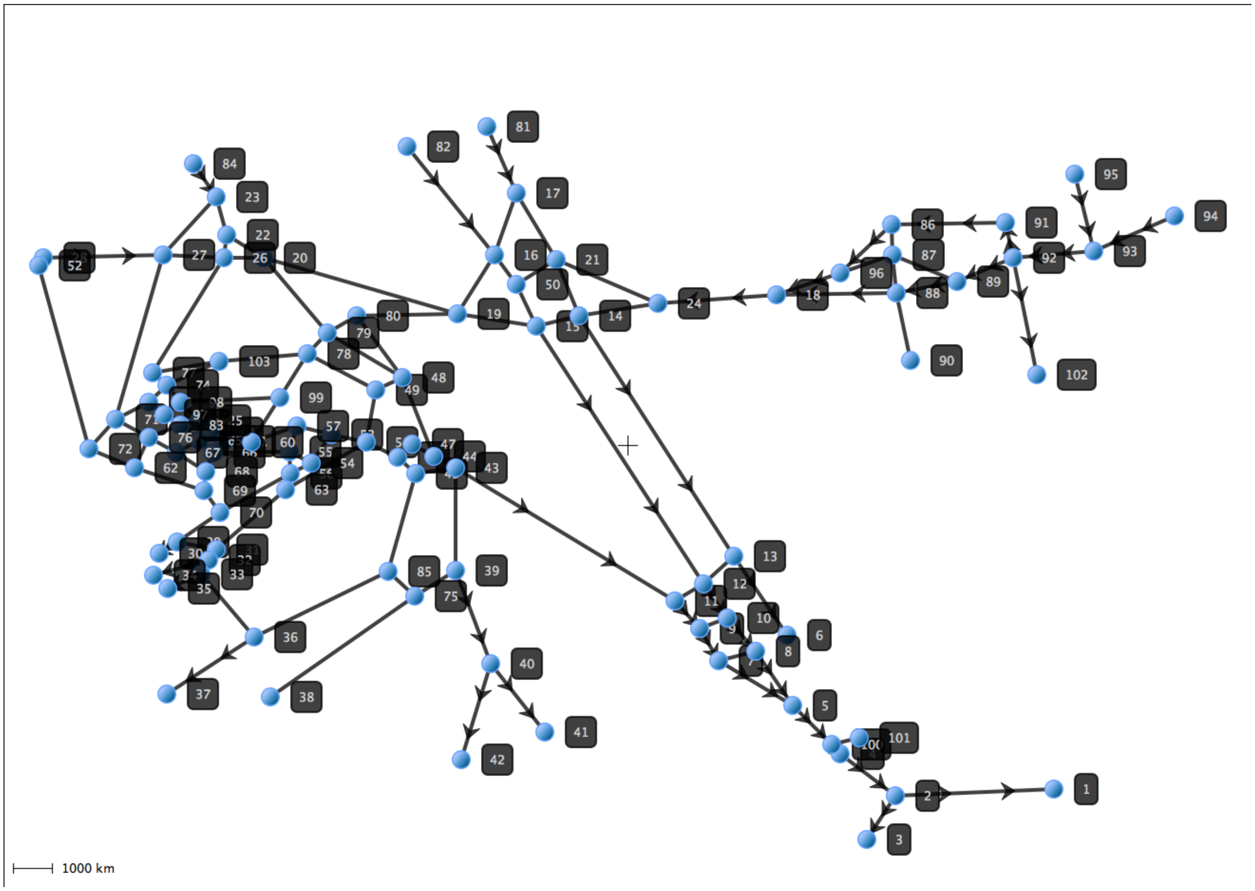

Figure 2. Fuel distribution network for lower Lafourche Parish and Houma, LA

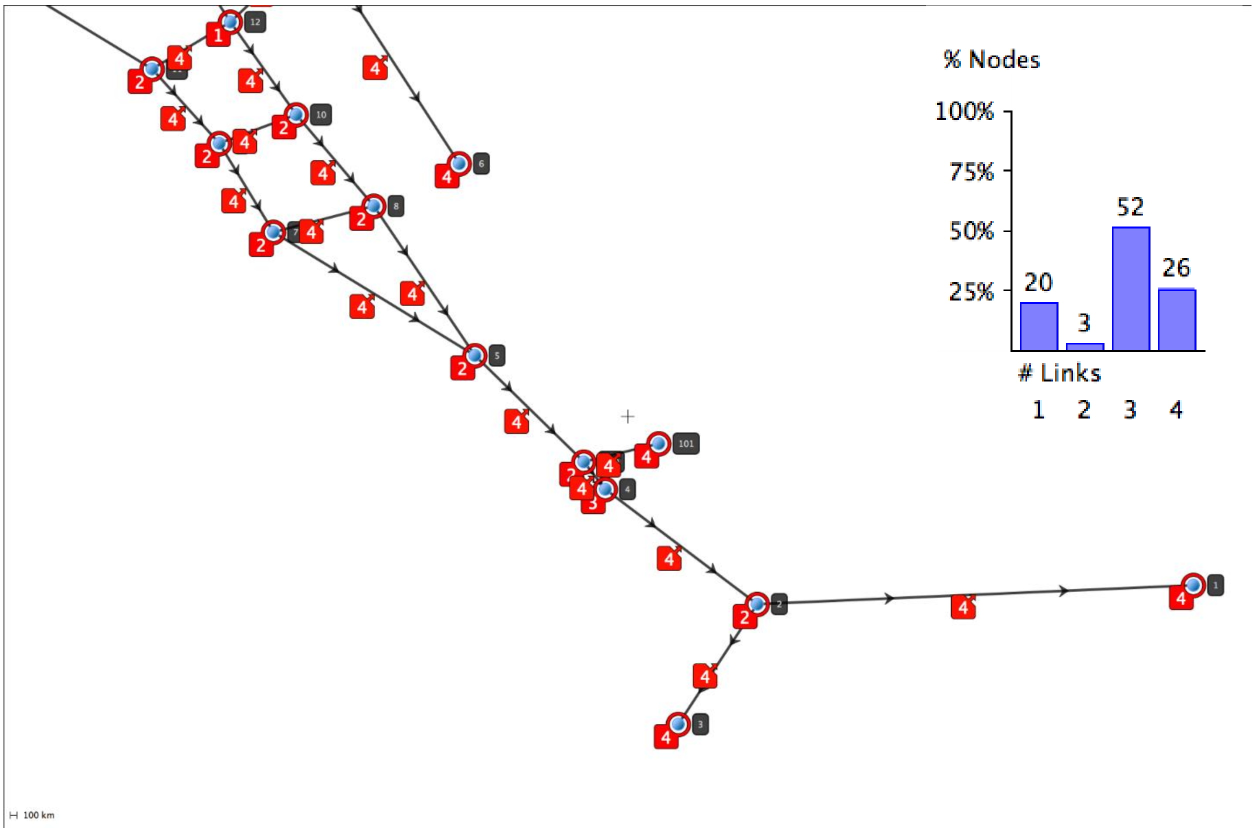

Figure 3. Coastal portion of network. Nodes labeled 4 have a single link attached, while nodes labeled 2 have 3 links attached. Inset is the histogram of the number of links per node for the entire network.

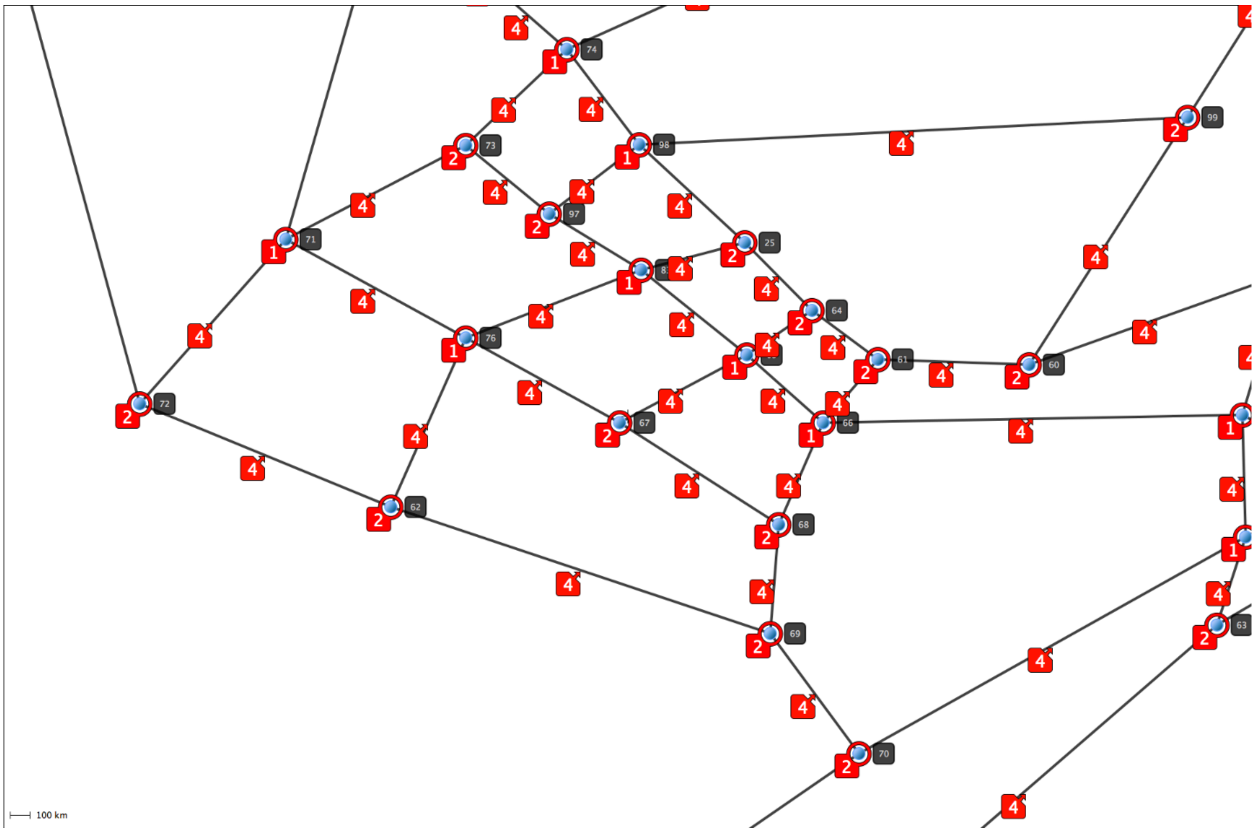

Figure 4. Urban portion of the network. Nodes labeled with degree ranking. Nodes labelled “1” most critical with 4 links connected.

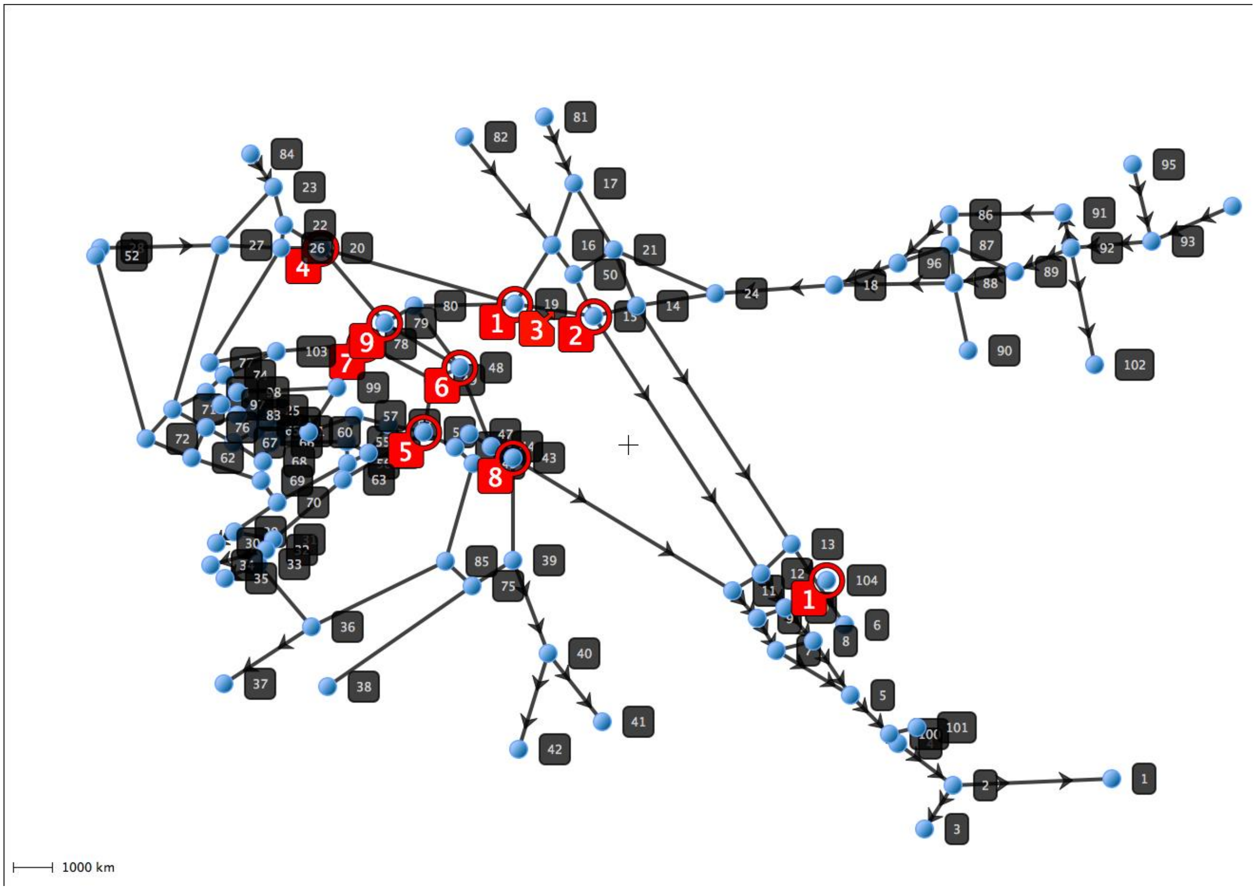

Figure 5. Nodes ranked by "betweenness", a measure of how many paths running through a node from all other nodes. Nodes with his betweenness are

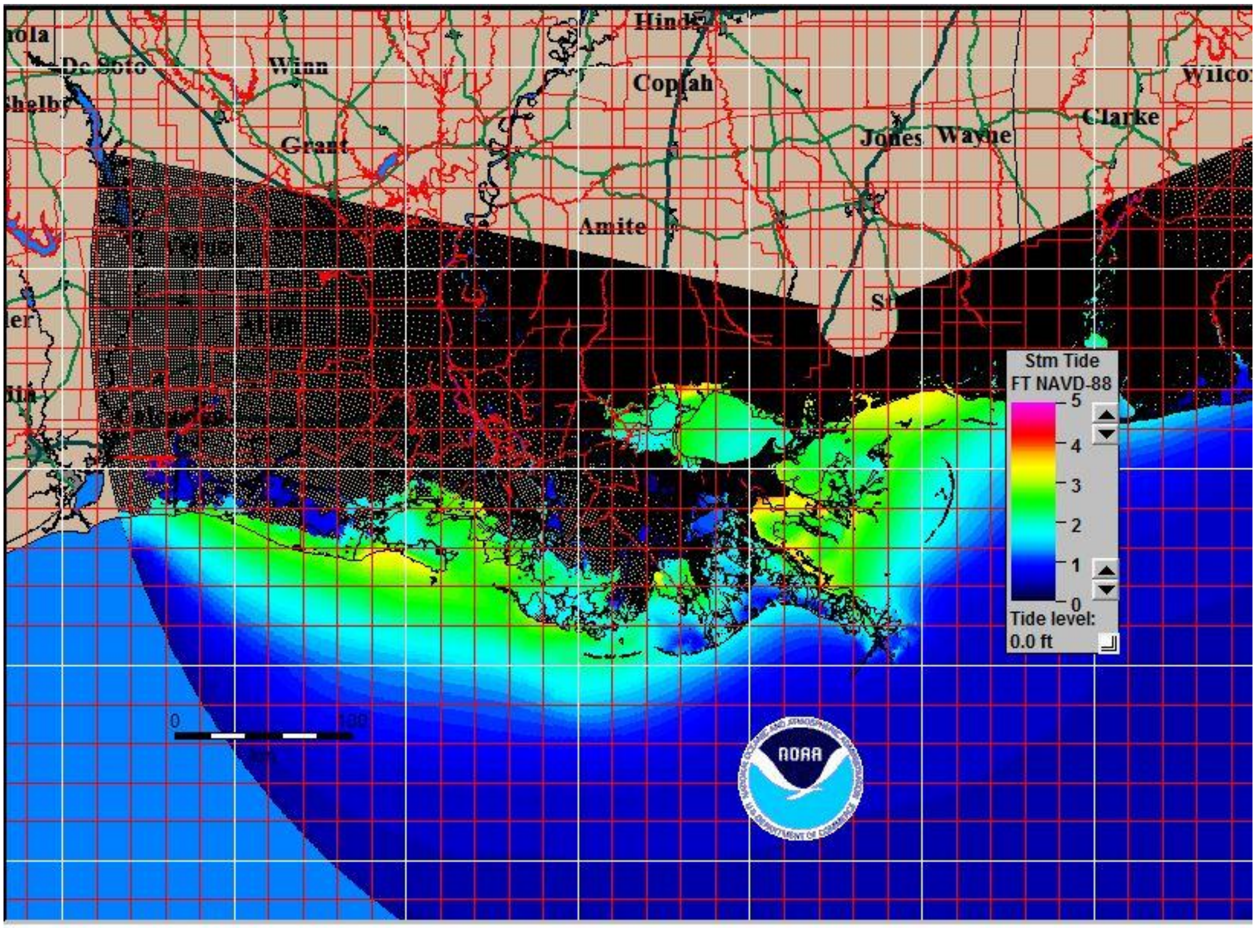

Figure 6. SLOSH Maximum Envelope of Water (MOM) tropical storm projection

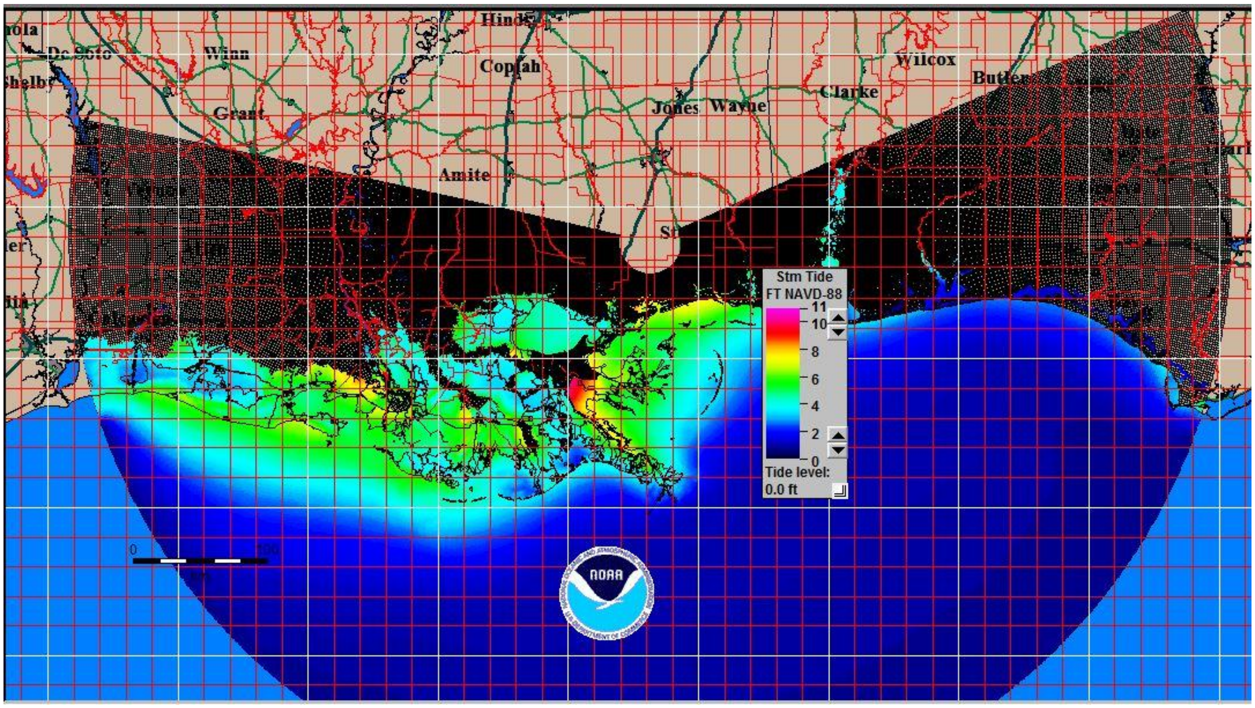

Figure 7. SLOSH Maximum Envelope of Water (MOM) Category One Storm Projection

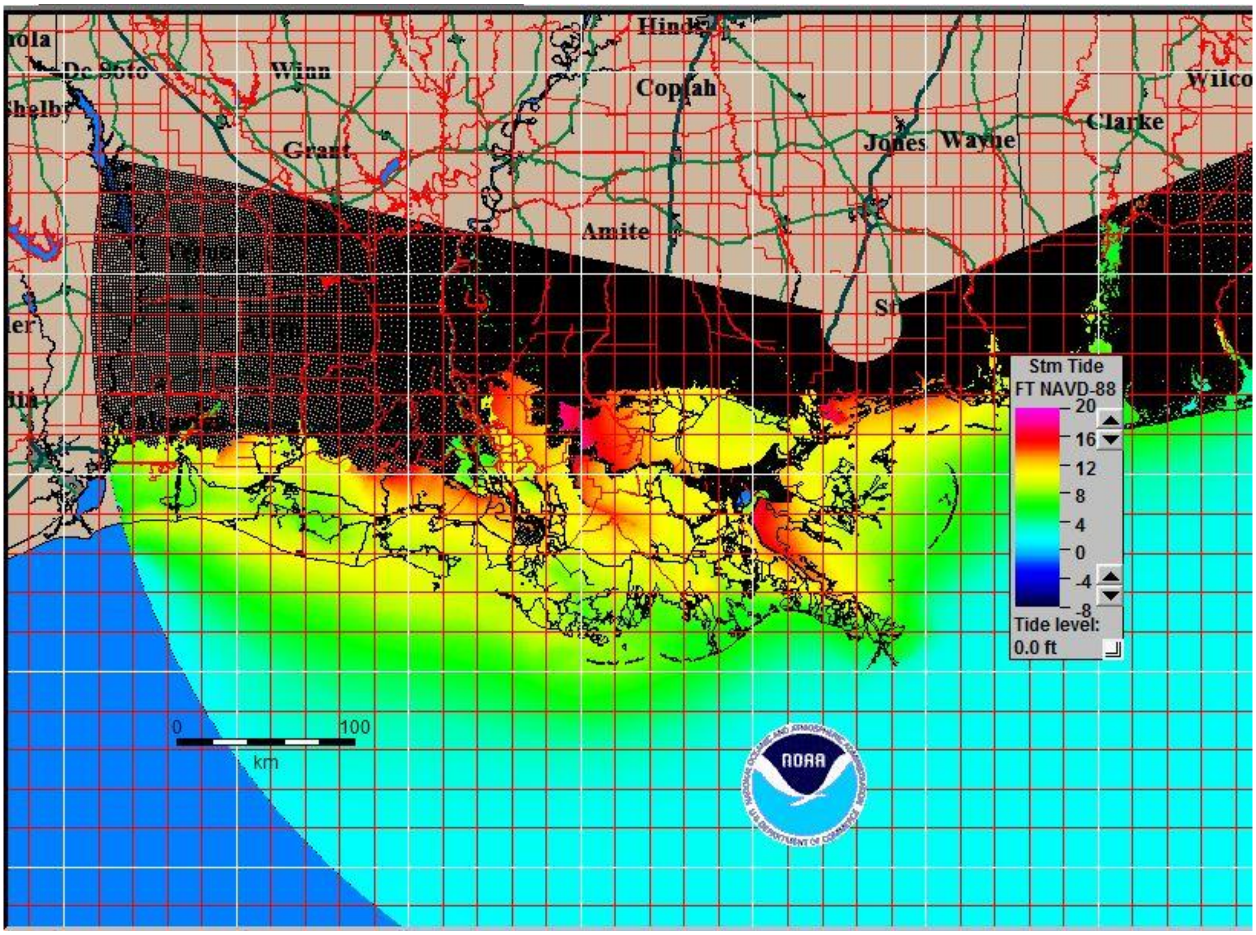

Figure 8. SLOSH Maximum Envelope of Water (MOM) Category Two Storm Projection

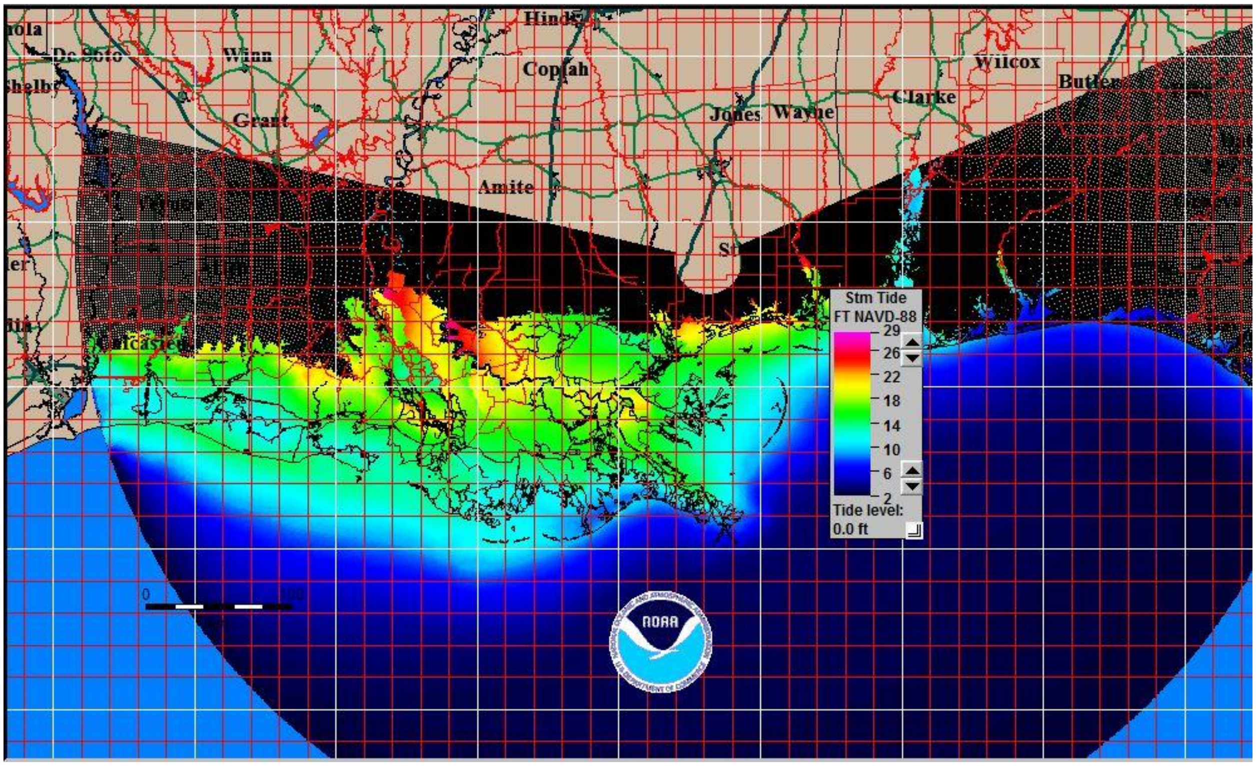

Figure 9. SLOSH Maximum Envelope of Water (MOM) Category Three Storm Projection

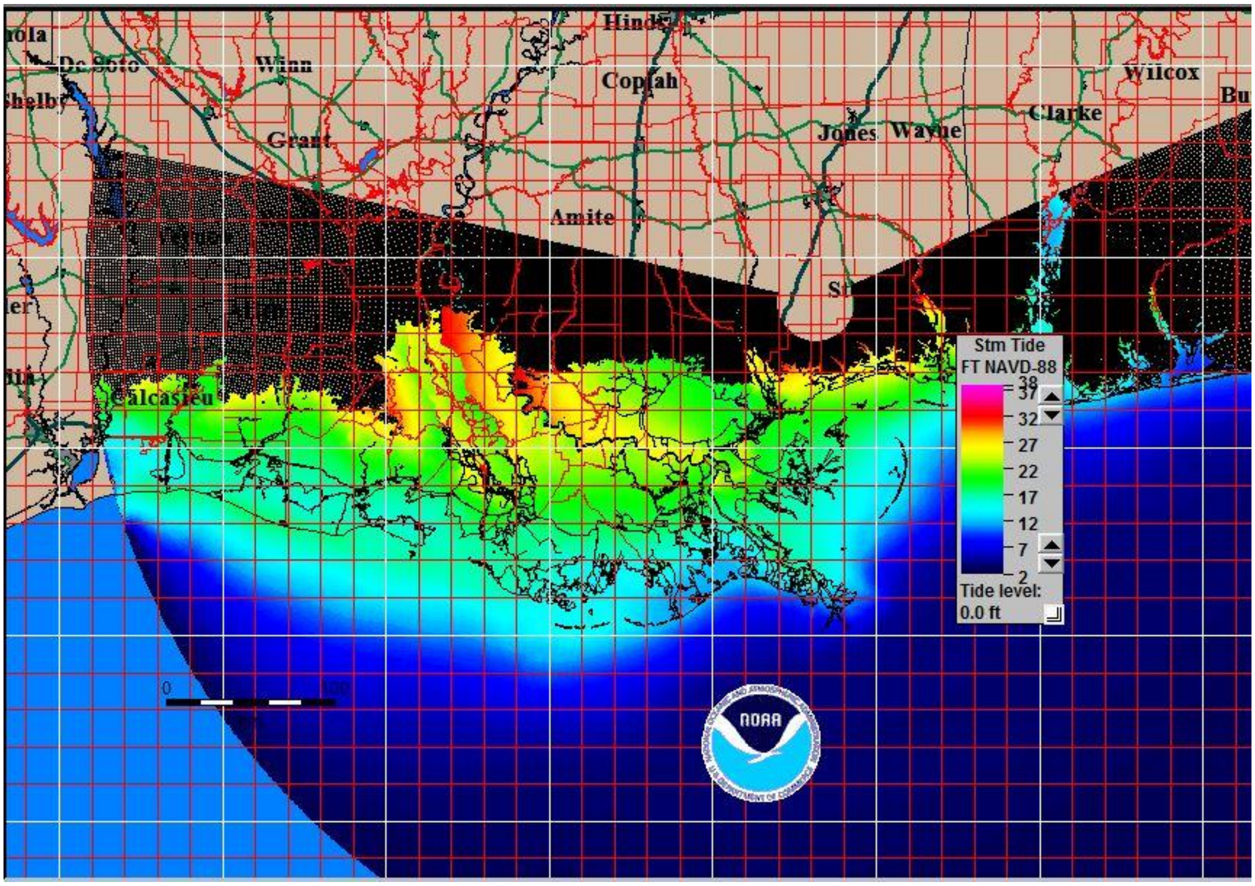

Figure 10. SLOSH Maximum Envelope of Water (MOM) Category Four Storm Projection

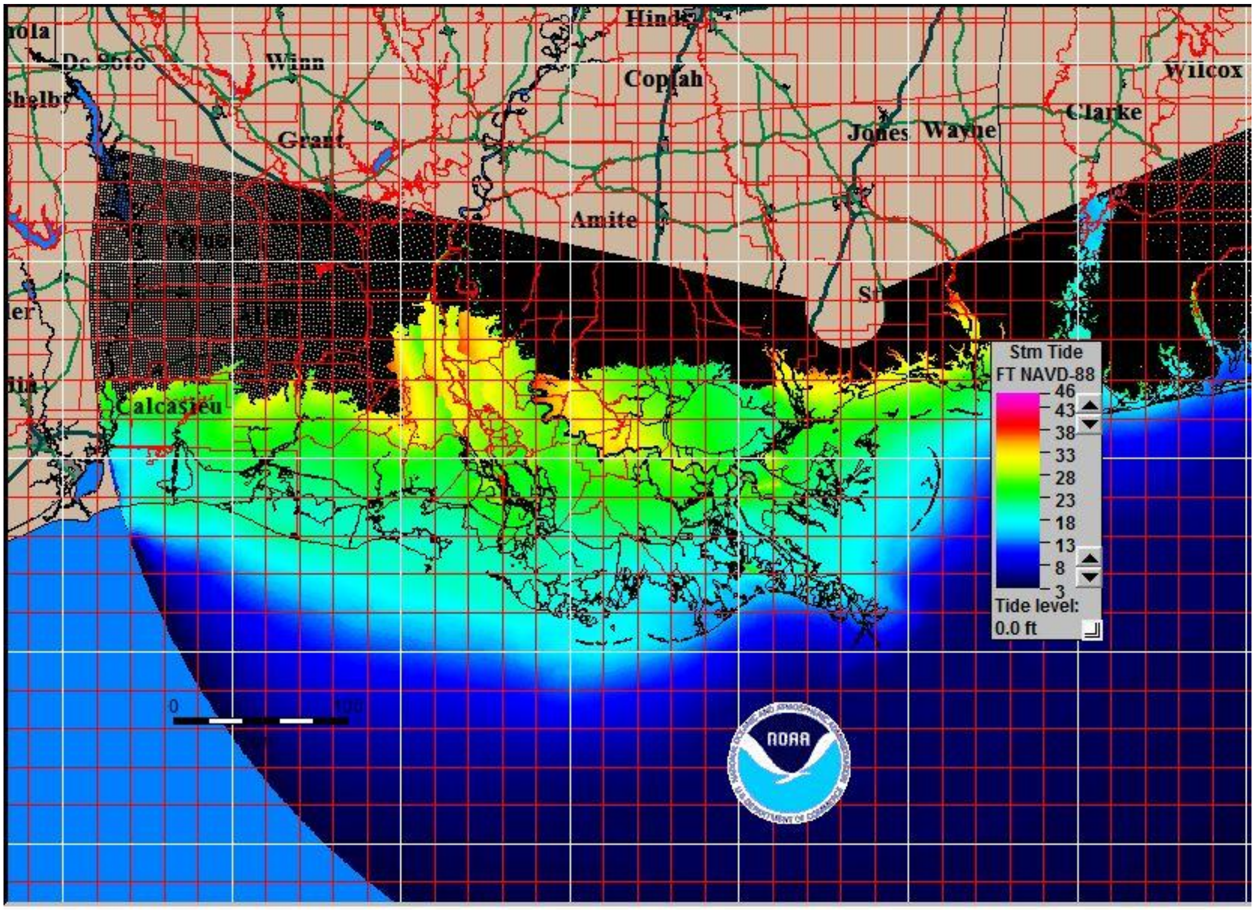

Figure 12. SLOSH Maximum Envelope of Water (MOM) Category Five Storm Projection