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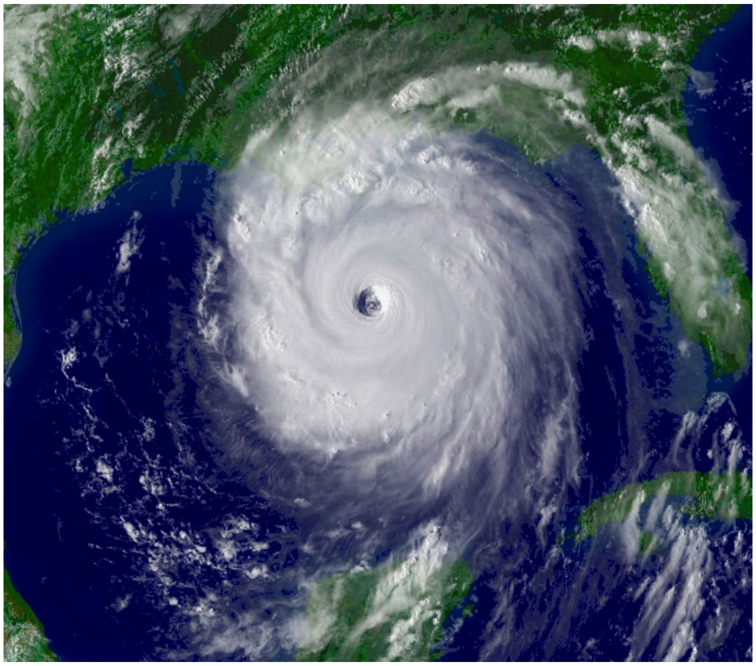

Spatial Analysis of Flooding and Dewatering of New Orleans during Hurricane Katrina

Fall 2018 Term Project

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CE 394 K 3 GIS in Water Resources

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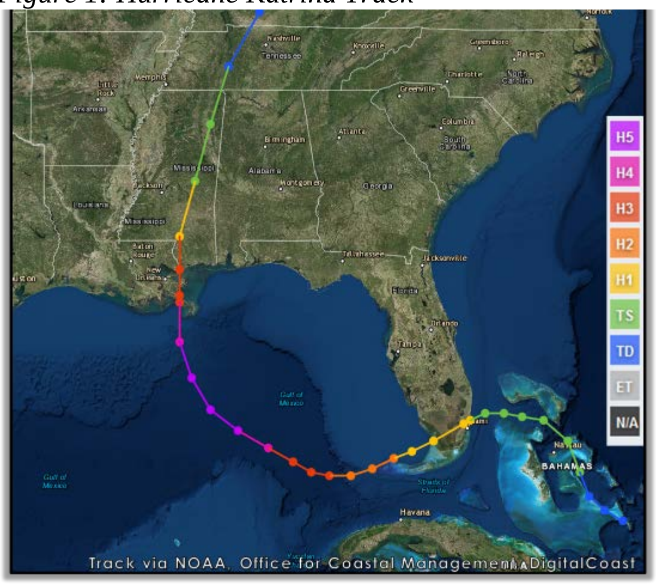
Introduction

One of the most unforgettable storms in US history, Hurricane Katrina wreaked havoc along the Gulf coast and Florida in August 2005. 1,833 deaths and $180 in damage were recorded (Medlin). The storm attained category 5 intensity with winds up to 175 mph in the Gulf of Mexico as it moved toward New Orleans, already bringing storm surge and heavy rainfall to the area. Katrina downgraded to a category 3 hurricane with winds up to 125 mph before making landfall on the Louisiana coast. FIGURE 1 shows the path of Hurricane Katrina. The warm August waters of the Gulf were able to strengthen Katrina in a short time, which is indicated by how quickly it turned from a category 3 to 5.

Figure 1: Hurricane Katrina Track



This project will focus on the story of Hurricane Katrina for the city of New Orleans, Louisiana. Although Hurricane Katrina was powerful in and of itself, the main reason Hurricane Katrina was devastating to New Orleans was because of its low elevation relative to immediate surrounding water bodies and an inadequate levee system that failed.

Location and Properties

New Orleans was originally a swamp sandwiched between Lake Pontchartrain and the Mississippi River. This area of New Orleans labeled in Figure 2 is bounded by the East Bank Levee System. A Digital Elevation Model (DEM) was developed using data from the National Elevation Dataset and portrayed in Figure 2. This DEM profile (in meters) includes elevation created by the levees. Both the lake and river sit at higher elevation than the majority of the city, making this study area a bowl-like shape. A DEM cut to the shape of the leveed study area is used for further analysis (shown in subsequent figures). Minimum and average elevation of the city (table 1) extracted from ArcGIS layer properties indicates that the majority of the city sits below sea level and ranges from 19 down to -8 meters below sea level.

Figure 2: DEM of New Orleans Area

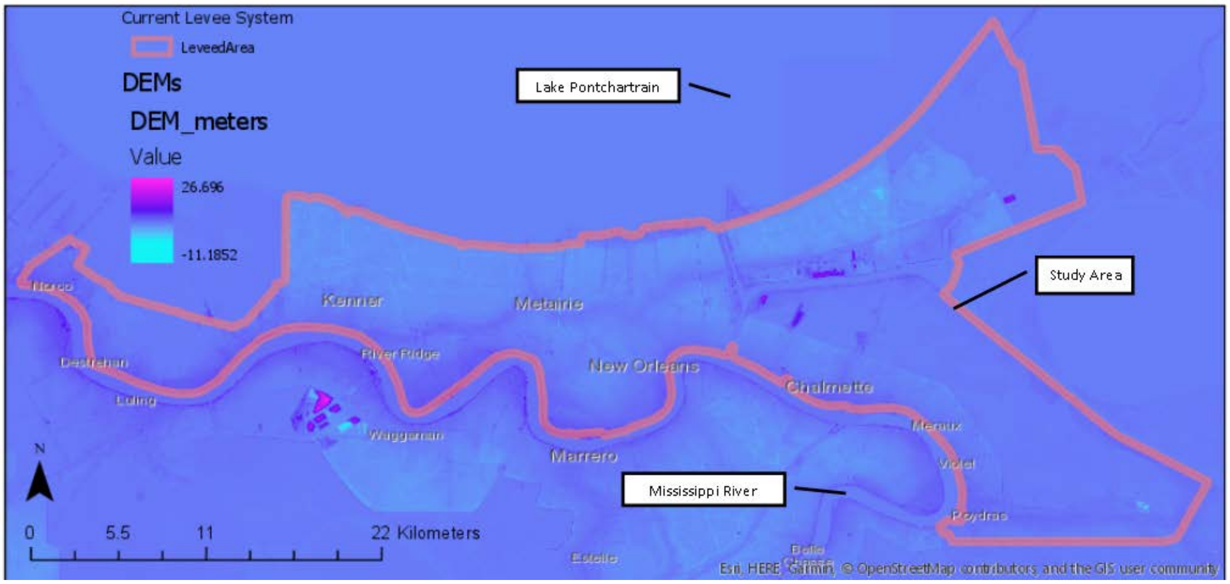
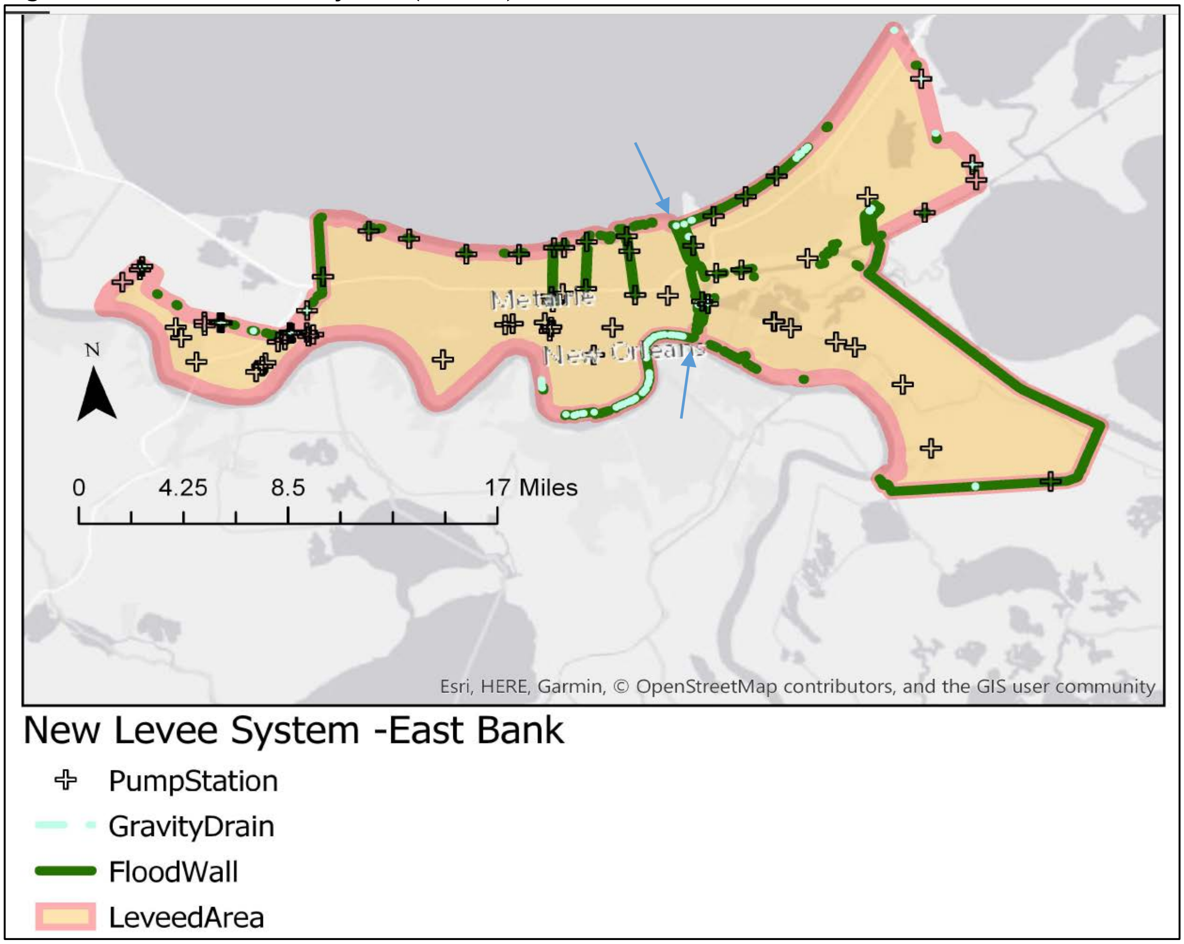


Table 1: DEM within Leveed Study Area

Minimum (m)	Maximum (m)	Mean (m)
-8.44	19.65	-0.028

The following Figure 3 is a map of the current East Bank levee system. These layers were imported from the US Army Corp of Engineers (USACE) website. The green flood wall components are taller levees typically made of reinforced concrete. There are pump stations throughout the city that pump water back into Lake Pontchartrain and Mississippi River. The Industrial Canal, also known as the Inner Harbor Navigation Canal (IHNC) travels between the blue arrows indicated in the figure. During Hurricane Katrina, the levees in New Orleans failed in three ways: they overtopped (water poured over top of the levees), breached (broke and released water), and scoured (weakened due to erosion and infiltrated water). Unfortunately, the USACE did not have digital layers of the levee system before Hurricane Katrina. However, the USGS conducted topographic surveys of major failed levees and released digital information on their locations, which was used as follows.

Figure 3: East Bank Levee System (current)



Spatial Analysis of Flooding

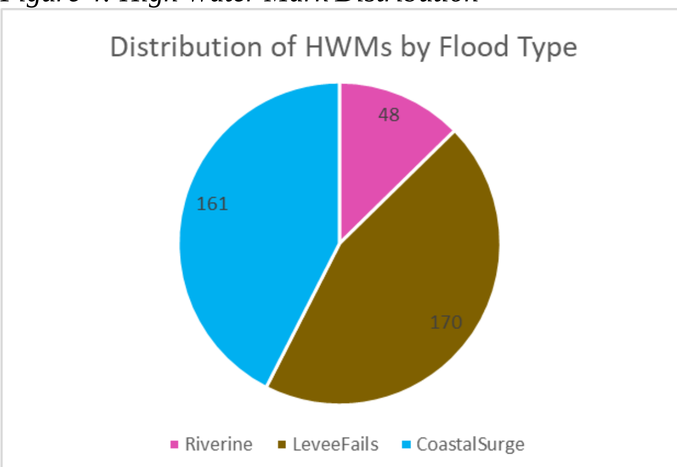
Flooding from Hurricane Katrina in New Orleans was spatially variant based on many factors, and this section will focus on the impact of levees failures and elevation profile.

The analysis will be based on High Water Marks (HWM) released by the Federal Emergency Management Agency (FEMA) on August 30, 2005. High water marks are marks left on buildings and other structures after a hurricane, indicated by mud lines, water lines, debris lines or wrack lines. HWMs may deviate from flood/stage height due to extraneous factors such as wind and shielding by other structures. Also, Hurricane Katrina destroyed many structures, making it difficult to access certain areas. Nevertheless, a large amount of points was collected to obtain a holistic analysis.

Analyzing HWM information from Katrina is important for preparing for future storms and future cost-benefit analysis. It is useful for updating flood insurance maps, water line maps, inundation maps for people and buildings. FEMA surveyed the greater New Orleans area, but only the data within the study area was used for my analysis. The HWMs were classified as caused by rainfall (‘Riverine-Hurricane’), related to levee issues (‘Levee-Break’), or caused by storm surge ('coastal storm surge only'). The distribution of these classifications is depicted in Figure 4, and further explained below:

1. Costal Strom Surge:
   These are HWMs caused by the surge level, the level that coastal waters rise to above their normal level due to waves and wind. There are a variety of origin types. HWMs can be caused by storm surge only, either by a level or angled surge level, by an un-even wave height or by wave-runups (the extension of a wave on the shore).
2. Levee Failures:
   This category includes HWMs caused by levees overtopping, breaching, or eroding. It also includes flooding that occurred due to the failure and inadequacy of drainage pumps.
3. Riverine-Hurricane:
   These are HWMs are caused by water level rise in a river, in this case, the Mississippi River.

Figure 4: High Water Mark Distribution



There are some limitations to this classification approach. First, the HWM collection and survey was done rapidly, and classifications were based on field observations, analysis of water mark angles and properties, and later reviewed using mapping resources. Also, flood dynamics are interconnected with domino effects, making it difficult to pinpoint a single cause to flooding in an area. For instance, surge rise from Lake Pontchartrain led to levee failures, and the surge may have potential to cause some of the damage marked as levee-related on its own. Some of the damage marked as surge-only also includes uncertainty because the damage may or may not have occurred with taller stronger levees regardless of storm surge intensity.

As seen in the distribution of HWMs, the majority of the damage is attributed to the failed levees, although damage attributed to storm-surge is almost as significant. The spatial distribution of FEMA flood types can be compared to the major "levee failure sites" 1 -6 marked by USGS. The USGS suggests that these were the major levee failures that caused the most damaging influx of water, mainly from Lake Pontchartrain. The USGS flagged major levee failure sites along with the HMWs according to their location and classification are depicted in figure 5.

I’ve identified four spatially distinctive regions marked as Region 1, 2, 3 and 4. HWMs in region 1 are predominantly coastal surge-related, which corresponds well to the lack of significant levee failures. In region 2, HWMs are predominantly marked as levee-related. This is also rational because the HWMs this area falls south of major levee failure sites 1 to 3. It is well documented that Lake Pontchartrain was the main culprit that led to levee damage and poured large amounts of water into the city, as opposed to Mississippi River or rainfall alone (Gesch; Smith). Therefore, levee failures 1 to 3 led to mainly levee-related damage in Region 2. However, there are a few coastal surge points marked at the east edge of region 2. This may be because lake water influx from levee failures may have failed to travel south-eastward, perhaps due to higher elevation lines (can be seen in the DEM) that blocked the levee-influx flow for that corner.

The HWMs in Region 3 are surge-related only because there were no major levee failures to the north of the area. Levee failures 4, 5 and 6 pushed the water south down the Industrial Canal and spilled water toward the southeast corner. This area is roughly labeled as region 4 and mainly labeled with levee-related HWMs. Throughout the study area, there are very few riverine-related HWMs. There are riverine-related HWMs near the Mississippi River in Region 2, but there are some near Lake Pontchartrain which are erroneous.

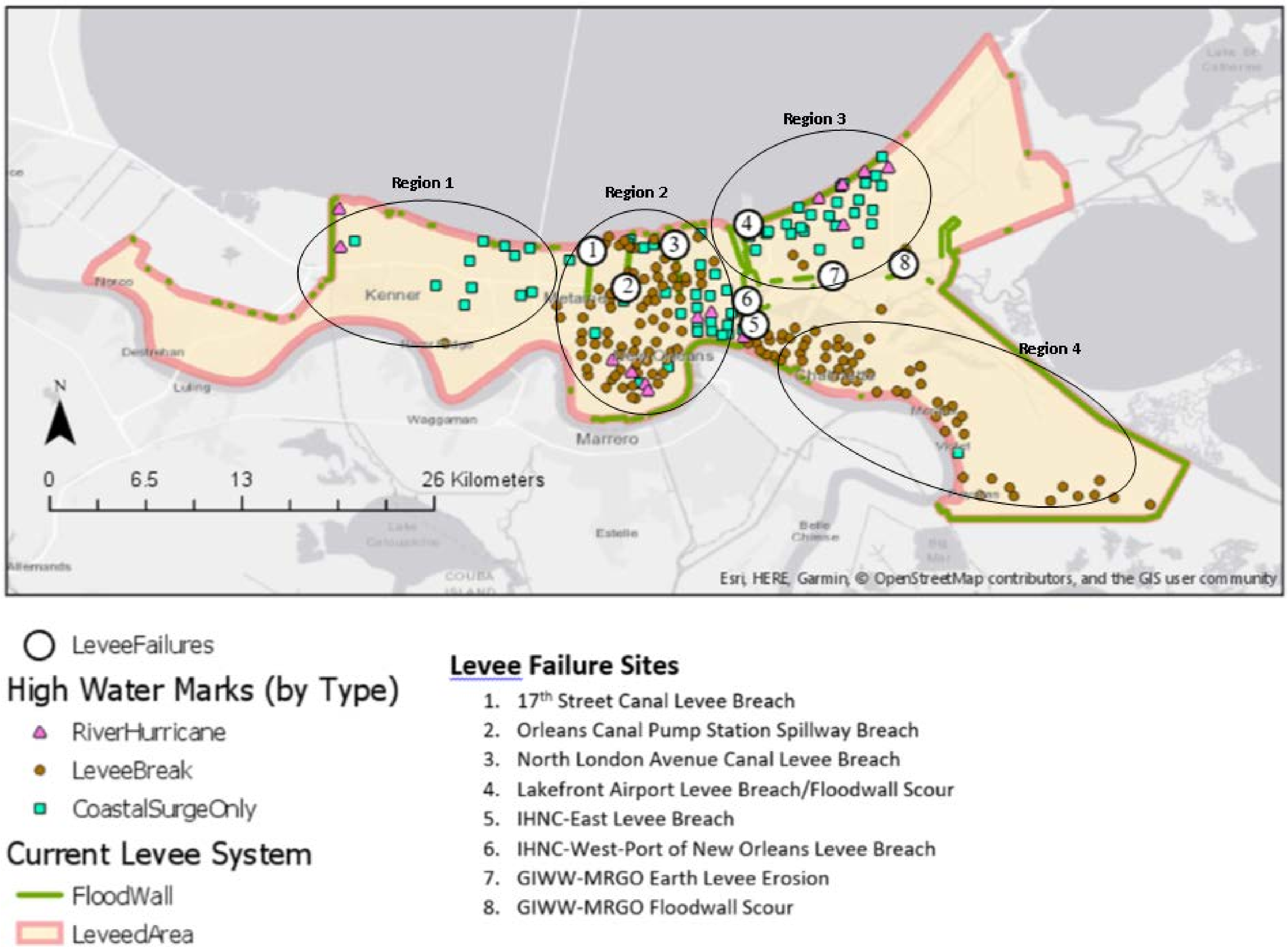


Figure 5: High Water Marks and Levee Failure Sites

[IHNC, Inner Harbor Navigation Canal (Industrial Canal); GIWW, Gulf Intracoastal Waterway; MRGO, Mississippi River Gulf Outlet]

It is important to examine the elevation dynamics in the DEM and its relationship to the magnitudes of the HMWs. In Figure 6, the HWMs which are measured relative to sea level like the DEM are shown, and are classified in 3 meter increments. In the next figure, the DEM is also classified in 3 m increments along with the HWMs, and the spatially distinct regions are marked again. From the classified DEM in figure 7, it is clear that the vast majority of the DEM is below 0 m. The edges of the study area have higher than 0 m elevation, and the area below -3 m is small and made up of features such as roads.

FEMA claims in its report that actual flood height is most likely higher than the HWMs left on buildings, because those marks may have been left by forceful waters, and waters with less force may still have inundated heights above recorded high water marks. For instance, in Region 1, where the elevation is largely at or below 0 m, but the HWMs are largely at -3 meters, it is safe to assume that the HWMs are an underestimation. One reason this could be is because the measurement might have been taken adjacent to a sink such as a road which buildings are usually surrounded by. Despite the underestimation, the distribution of HWMs across the study area allows us to compare the spatial impact on HWM magnitude.

Regions 1-3 lie mostly lie on the range of -3 to 0 m, and can be compared with each other. Region 2 has the highest magnitude of HWM height at up to 3 m, followed by Region 3 at up to 0 m and Region 1 at up to -3 m. Knowing that the central Region 2 is encompassed by the major levee failures, it appears that the influx of Lake Pontchartrain water after levee failures was a major contributor to the damage there. Part of Region 4 sits at higher elevation, and HWMs at higher elevation will have higher heights, and need to be corrected by elevation. However, even at less than 0 m elevation, there are high HWMs recorded in this region. This may be due to the significance of the Industrial Canal avenue breaches (5 and 6). The Industrial Canal is the major pathway for water from Lake Pontchartrain, and hence these breaches provided a forceful influx of water, damaging region 4.

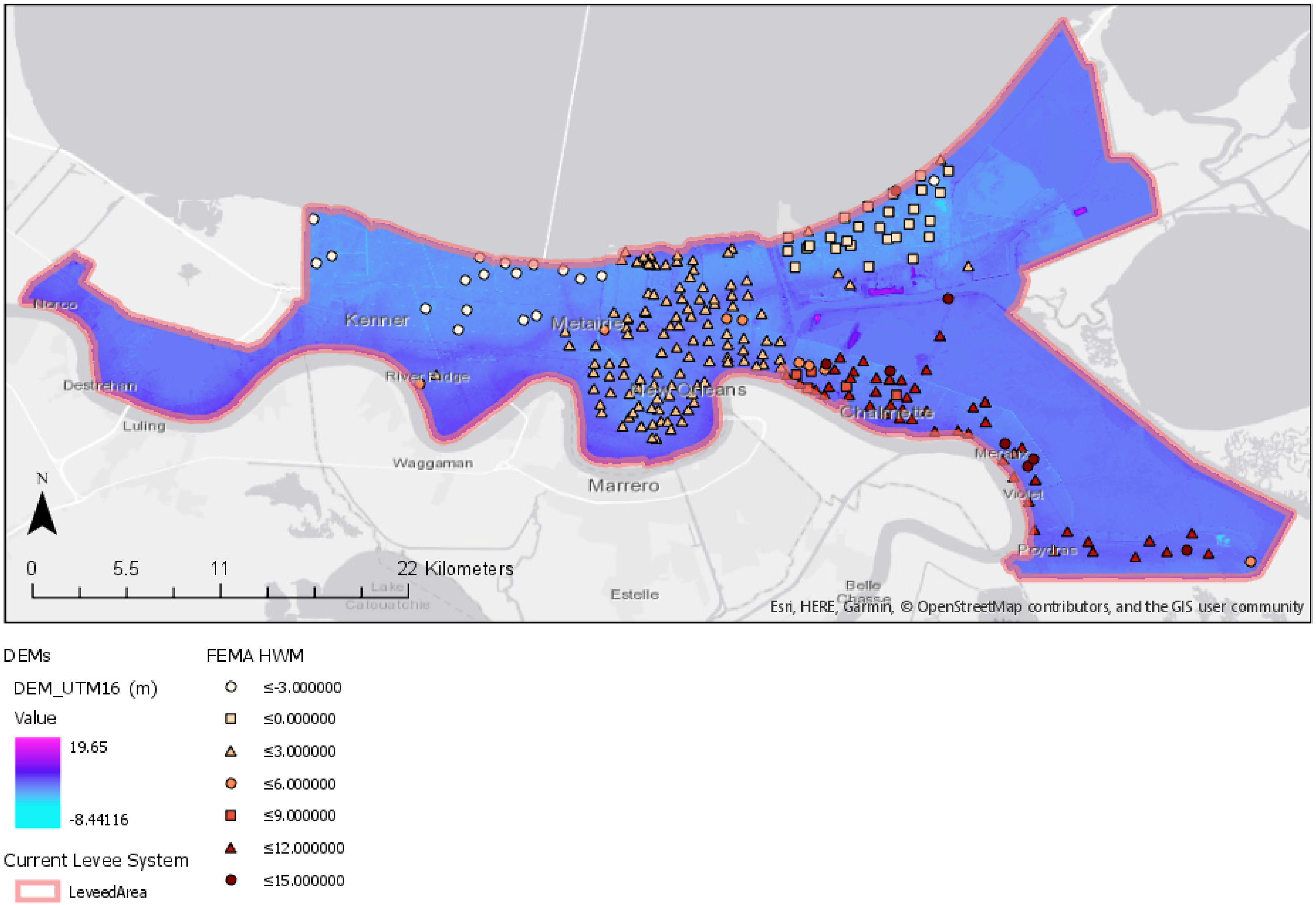


Figure 6: HWM magnitudes and DEM

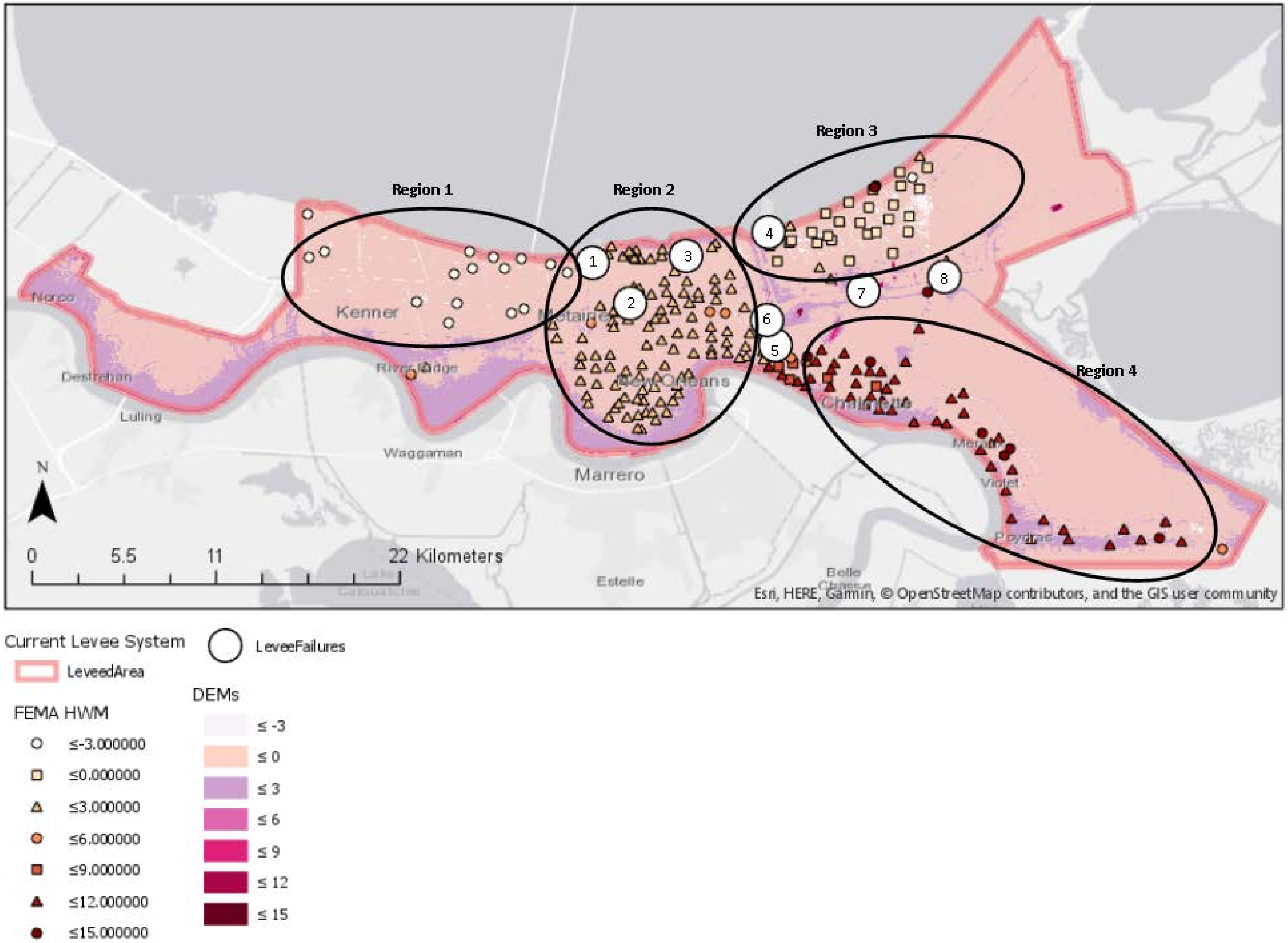


Figure 7: HWM magnitudes and incremental DEM

In summary, regions 2 and 4 experienced high flood marks and had the most damage from levees. Levee-related HWMs had a higher average HWM (as seen in Table 2) than surge-related average HWM. Although the average riverine HWM is high, it is because most of the riverine-based HWMs are on levee structures or embankments, which are at higher elevation, making them non-comparable. There were four riverine–HWMs above 20 m which I manually removed (Table 3) due to their unrealistically high magnitude. These HWMs may have been present due to water splashes on tall structures, but are not indicative of flood depth.

Table 2: Average HWMs

	Avg HWM (m)
Riverine	7.08
LeveeFails	5.98
CoastalSurge	4.88

Table 3: Removed Points

Points removed from Analysis		
Type: Riverine		
HWM (m)	Latitude	Longitude
95.2	30.720711	-90.083432
76.5	30.670099	-90.001615
67.4	30.76199	-89.831306
62.4	30.703549	-89.848047
27.9	30.394586	-89.893528
22.5	30.323686	-89.753897

Spatial Analysis of Dewatering Efforts

New Orleans filled up like bowl from the excess amount of water from Hurricane Katrina. Details of flood dewatering of the city is complex, dynamically involving various variables like rate of water pouring in from Lake Pontchartrain, rate of pumping water out, and precipitation that continued for days during Katrina. Engineers were at work fixing the levees and broken pumps, and the rate at which these actions happened also impacted dewatering. One of the most useful tools and insights for dewatering is quantifying the volume of water that accumulated that needed to removed, and quantifying the area impacted by these volumes. This analysis was done in GIS using the DEM and associated GIS tools on the raster. First, the DEM was projected to the UTM-16 Zone to obtain equal area zones. All other GIS layers were also projected to UTM-16 zone for consistency. The projected DEM properties are summarized in Table 5.

Table 4: Projected DEM Properties

Columns	6616
Rows	3465
Number of Bands	1
Cell Size X	9.89950387499423
Cell Size Y	9.89950387499417

Given the projected cell size in meters, the area of one cell is 98 m2. The raster was divided into discrete integers using the raster calculator tool. Then, the cumulative count of the number of cells of each 1 m elevation increment was used to calculate cumulative area and volume as shown in Table 6. The cumulative area (in km2) and volume (billions of gallons) is depicted in Figure 8.

As seen in the graph, the majority of the volume of water that potentially fills up in New Orleans is below 0 m. This is expected since the vast majority of the subject area is at or below 0 m. From -3 to 0 m, there is a volume difference of nearly 140 billion gallons. And the area within the city below 0 m is over 500 km^2. These are potential volumes. Calculating actual volumes requires information on maximum or average elevation to which the water rose, which varies dramatically especially in urban locations.

The USGS took estimates of maximum elevations to which the water rose on August 30, September 2, September 7 and September 15, 2005. Based on these, estimated volumes were calculated for 4 different Pumping Cells (PC) within New Orleans. These PCs were indicated by ASCE as distinctive levee-protected areas (Figure 9). The estimated volume at each PC on each day is summarized in Table 6. Unfortunately, digital layers for these PCs or data on the specific stage heights that USGS used at each PC and day was not available for me to conduct a volume analysis by region. However, Figure 9 gives insight to and validates the spatial patterns that are being analyzed in this report.

Table 5: DEM Calculations

Elevation (m)	Count	Cumlt Count	Cumlt Area (km2)	Cumlt Volume (billion gallons)
-8	1	1	0.000098	2.58916E-05
-7	215	216	0.021168	0.005592586
-6	1978	2194	0.215012	0.05680617
-5	1513	3707	0.363286	0.095980161
-4	19857	23564	2.309272	0.610109662
-3	35001	58565	5.73937	1.516341554
-2	369042	427607	41.905486	11.0714294
-1	1110316	1537923	150.716454	39.81928715
0	3799826	5337749	523.099402	138.202862
1	702025	6039774	591.897852	156.3794125
2	276382	6316156	618.983288	163.5353847
3	103886	6420042	629.164116	166.2251594
4	24073	6444115	631.52327	166.8484479
5	10605	6454720	632.56256	167.1230284
6	5495	6460215	633.10107	167.2653027
7	4493	6464708	633.541384	167.3816337
8	3440	6468148	633.878504	167.4707008
9	2298	6470446	634.103708	167.5301997
10	2511	6472957	634.349786	167.5952135
11	1134	6474091	634.460918	167.6245745
12	483	6474574	634.508252	167.6370802
13	343	6474917	634.541866	167.645961
14	297	6475214	634.570972	167.6536508
15	118	6475332	634.582536	167.656706
16	160	6475492	634.598216	167.6608487
17	65	6475557	634.604586	167.6625316
18	33	6475590	634.60782	167.663386
19	5	6475595	634.60831	167.6635155

Figure 8: Cumulative Area and Volume

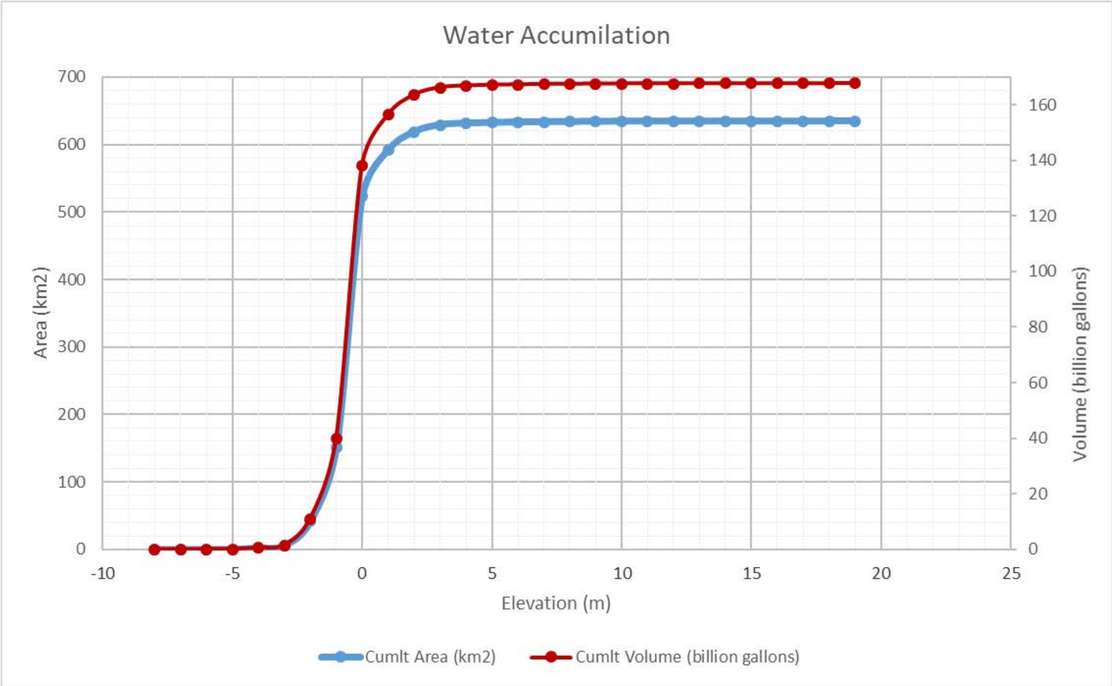


Figure 9: Pumping Cells

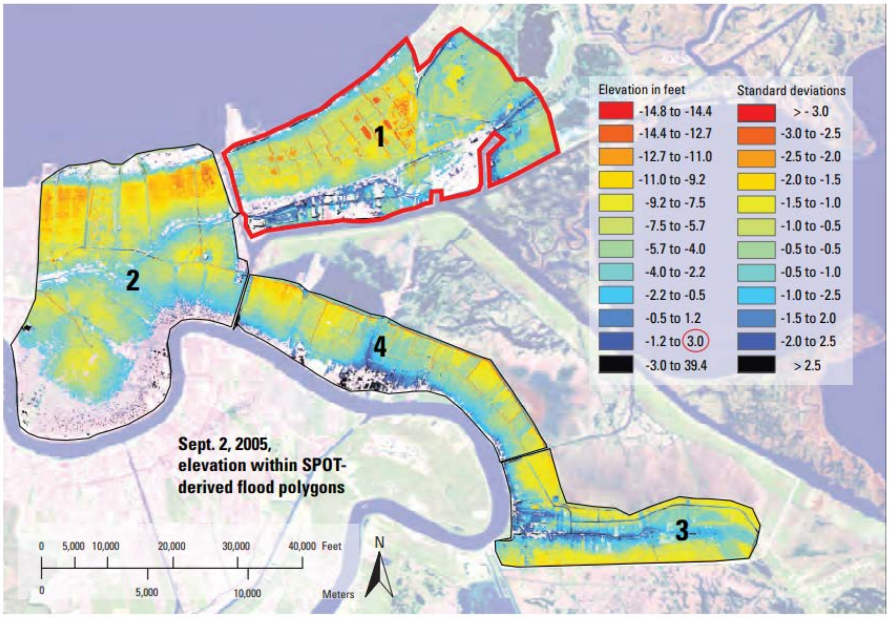


Table 6: Volumes by Pumping Cell and Date (gallons)

	Aug. 30	Sept. 2	Sept. 7	Sept. 15
PC 1	26,733,419,000	43,318,140,000	41,127,626,000	16,630,714,000
PC 2	44,932,760,000	52,012,307,000	32,184,081,000	20,646,631,000
PC 3	0	13,361,664,000	10,266,968,000	11,584,261,000
PC 4	13,364,200,000	22,073,107,000	15,351,355,000	7,325,834,000
Total	85,030,379,000	130,765,218,000	98,930,030,000	56,187,440,000

PC 2 is equivalent to my Region 2, and had the highest volumes of accumulated water and was most impacted by flooding as seen from Table 7. PC 1 which is equivalent to my Region 3 had the second highest amount of accumulated volume. PC 3 and 4 is collectively my Region 4, and it had a smaller amount of volume than PC1/Region3, expect on September 15.

PC 3 did not flood immediately due to its distance from Lake Pontchartrain and the major levee failures. Pumping may have been ideal in this region. PC 3 had flooded by September 2 and together accumulated a large amount of volume in Region 4 (PC 3 and 4) that drained at a slower rate than other regions. The area of each PC is not identical, and volume will be proportional to PC size. However, based on visual inspection, the size of PC 1, 2 and 3+4 appear roughly similar enough for this volume analysis.

Flood waters accumulated in all regions until September 2, at which point the storm conditions alleviated and pumping systems were made to run more efficiently. Another USGS report conducted a topographical analysis based on the assumption that flood waters in the city had reached equilibrium with the height of Lake Pontchartrain on September 2, after which they started decreasing (Gesch, 2005). On September 2, the USGS gage height of Lake Pontchartrain was 2.37 ft or 0.72 m above NAVD88 zero elevation. Based on the chart from Figure 8, at 0.72 m, there is an accumulated volume of 140 billion gallons of water and around 570 km2 of land impacted throughout the city. This is a realistic volume compared to the total September 2 volume from table 7, which is smaller because it only includes the four PCs, whereas my estimate includes the entire city.

Conclusions

Parameters discussed in previous sections is summarized below in Table 7. Region 1, the western portion of New Orleans was impacted least by flooding, due to low high water marks observed in the city on August 30, 2005. Majority of the impact here in this region is due to coastal surge. Region 2, the central portion of the city was most heavily impacted by flooding proven by high HWMs and the most accumulated volume compared to other areas. Damage here is attributed to levee failures. The damage in region 3 was attributed to coastal surge rather than levee failures, and the damage in region 4 to levee failures. Both regions experienced high volume accumulation, but took longer to accumulate and longer to dewater in region 4 than region 3. Overall, the city was trying to dewater approximately 140 billion gallons of water that had accumulated throughout the city. Although storm surge was extreme, the damage was more severe due to levee failures, since the HWMs marked as levee-related have the highest flooding magnitude and water accumulation by volume. A spatial pattern of flooding and dewatering resulted from the elevation profile, from distinct leveed regions that isolated water, and due to the direction and magnitude of water influx from levee failures. New Orleans was heavily inundated from Hurricane Katrina, and different parts of New Orleans were impacted in different ways.

Table 7: Summary of HWMs by Region

Region	PC	HWM Type	HWM Magnitude (m)	Predominant Elevation (m)	Volume (billion gals)	Volume (billion gals)
			August 30, 2005			September 15, 2005
1	N/A	Coastal Surge	≤ -3	≤ 0		
2	2	Levee-Related	≤ 3	≤ 0	45	21
3	1	Coastal Surge	≤ 0	≤ 0	27	17
4	3, 4	Levee-Related	≤ 12	≤ 0-3	13	20

References

Collins, B.D., Kayen, R., Minasian, D., and Reiss, T., 2009. Terrestrial lidar datasets of New Orleans, Louisiana, levee failures from Hurricane Katrina, August 29, 2005: U.S. Geological Survey Data Series 470, 24 p. and data.

FEMA Report, High Water Mark Collection for Hurricane Katrina in Louisiana (March 30, 2006), https://www.fema.gov/pdf/hazard/flood/recoverydata/katrina/katrina_la_hwm_public.pdf.

Gesch, D., Topography-based analysis of Hurricane Katrina inundation of New Orleans: Chapter 3G in Science and the storms—the USGS response to the hurricanes of 2005: U.S. Geological Survey Circular 1306, 283 p.

Medlin, J., (November 2016) Extremely Powerful Hurricane Katrina Leaves a Historic Mark on the Northern Gulf Coast, https://www.weather.gov/mob/katrina.

Smith, J., Rowland, J., Temporal analysis of floodwater volumes in New Orleans after Hurricane Katrina: Chapter 3H in Science and the storms—the USGS response to the hurricanes of 2005: U.S. Geological Survey Circular 1306, 283 p.