Storm surge issues of Hurricane Katrina

Pat Fitzpatrick, Yongzuo Li, Sachin Bhate, and Yee Lau
GeoResources Institute
Mississippi State University
Stennis Space Center branch

Ben Jelley and Elizabeth Valenti
WorldWinds, Inc.
Stennis Space Center, MS

Bob Jacobsen
URS
Baton Rouge, LA

Comparison: Camille to Katrina

	Camille	Katrina
Intensity (sustained winds and pressure)	Estimated 190 mph 909 mb (26.84 in. mercury)	125-135 mph in Buras, LA landfall 120-130 mph at MS landfall 918 mb (27.11 in. mercury) in Buras landfall 927 mb (27.37 in. mercury) in MS landfall
Eye size	10 miles	35 miles
Distance hurricane-force winds from storm center	60 miles	120 miles
Distance tropical storm-force winds from center	180 miles	230 miles
Translation speed	18 mph	15 mph
Fatalities	172 in Mississippi 9 in Louisiana 114 in Virginia 2 in West Virginia	200 In Mississippi 1300 in Louisiana 6 in south Florida 1 in Georgia Hundreds missing
Maximum storm surge	25 feet in Pass Christian, 10-20 feet to Pascagoula 15-25 feet in east Louisiana marsh	28-31 feet in Waveland and Bay St. Louis, 17-22 feet along east MS, 8-15 feet in AL, 15-20 feet in east Louisiana marsh and Slidell, 10-15 feet Lake Pontchartrain

Outline

- Storm surge physics
- Determining storm surge evolution with data and a numerical model
- Timing of wind and surge
- Overview of Louisiana levee failures
- Influence of the Mississippi River Gulf Outlet
- Conclusions

I. Storm surge physics

Factors contributing to surge

Water height depends on complex interaction of several factors, including:

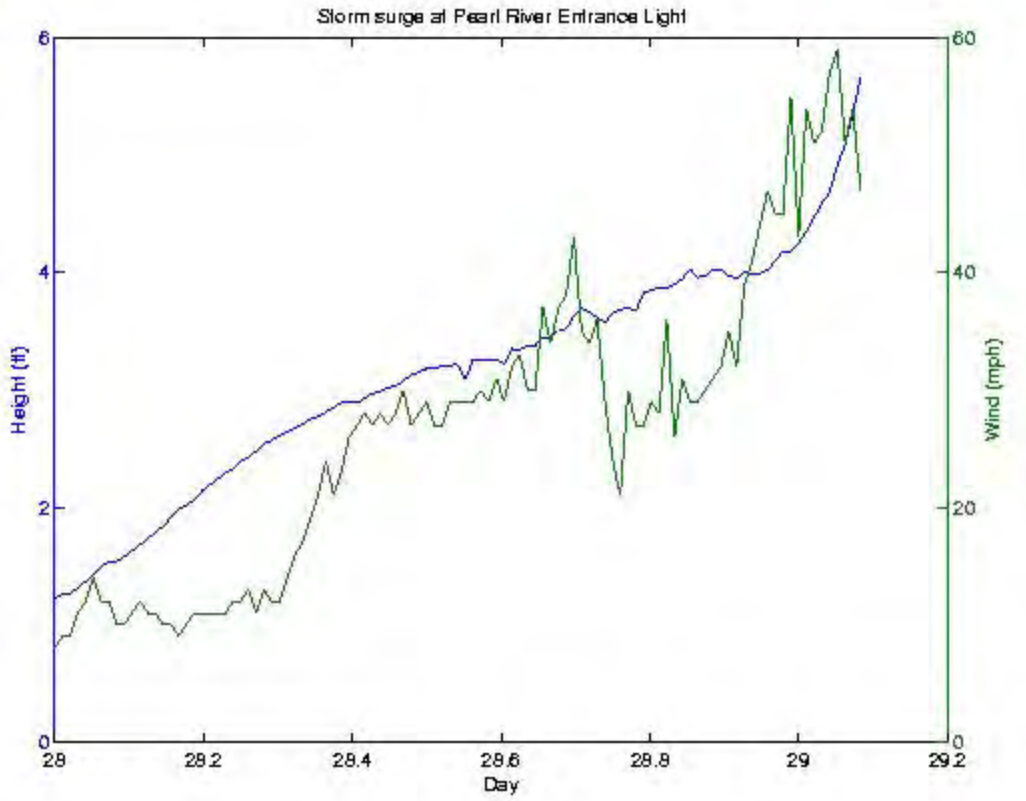
- size, defined as the radius of tropical storm-force winds
- central minimum pressure
- speed of motion of the system
- bathymetry near the storm's landfall point
- astronomical tides
- wave setup
- steric effect
- local topography
- maximum wind speed
- man-made levees?

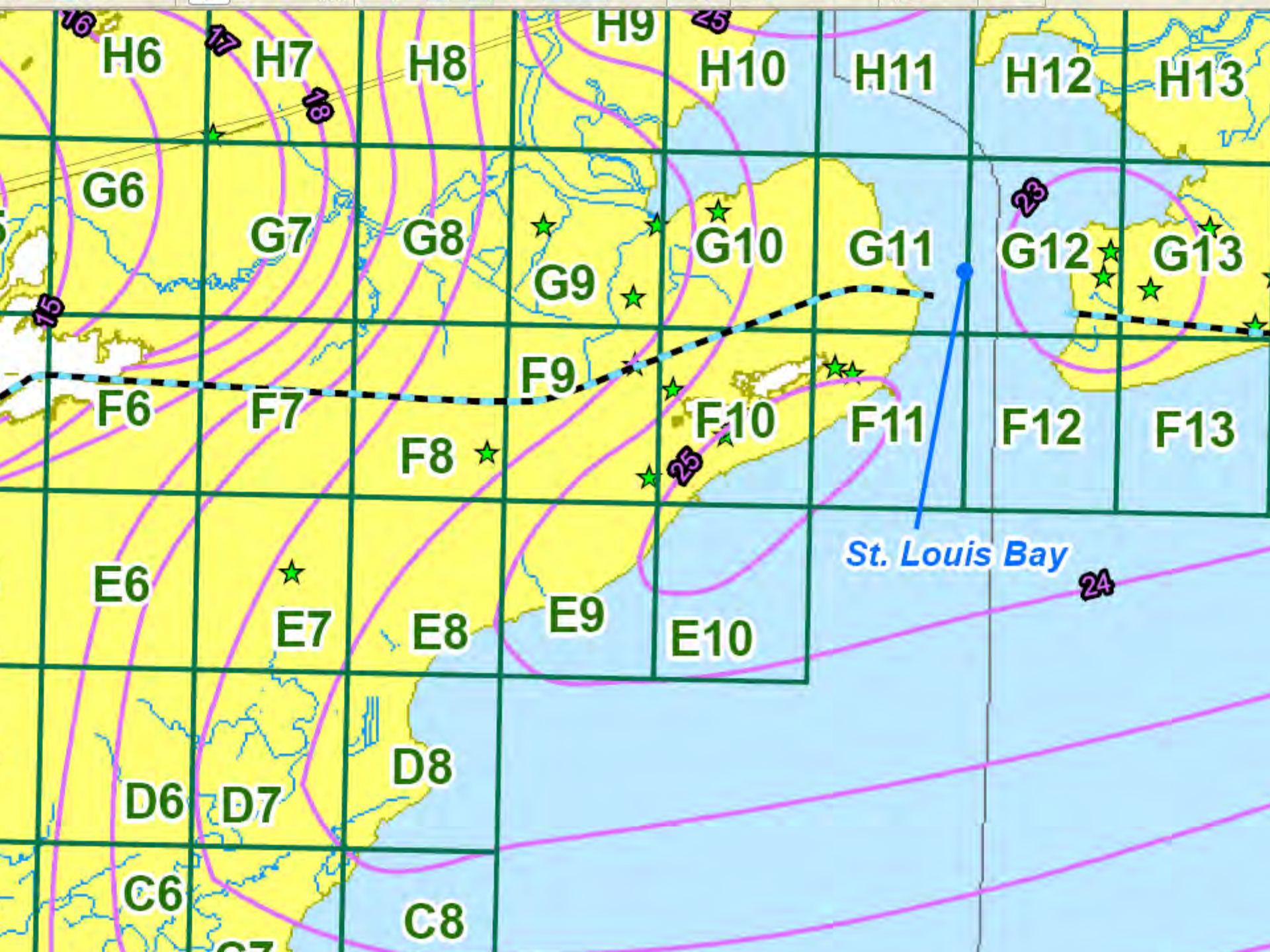
II. Determining storm surge and its evolution

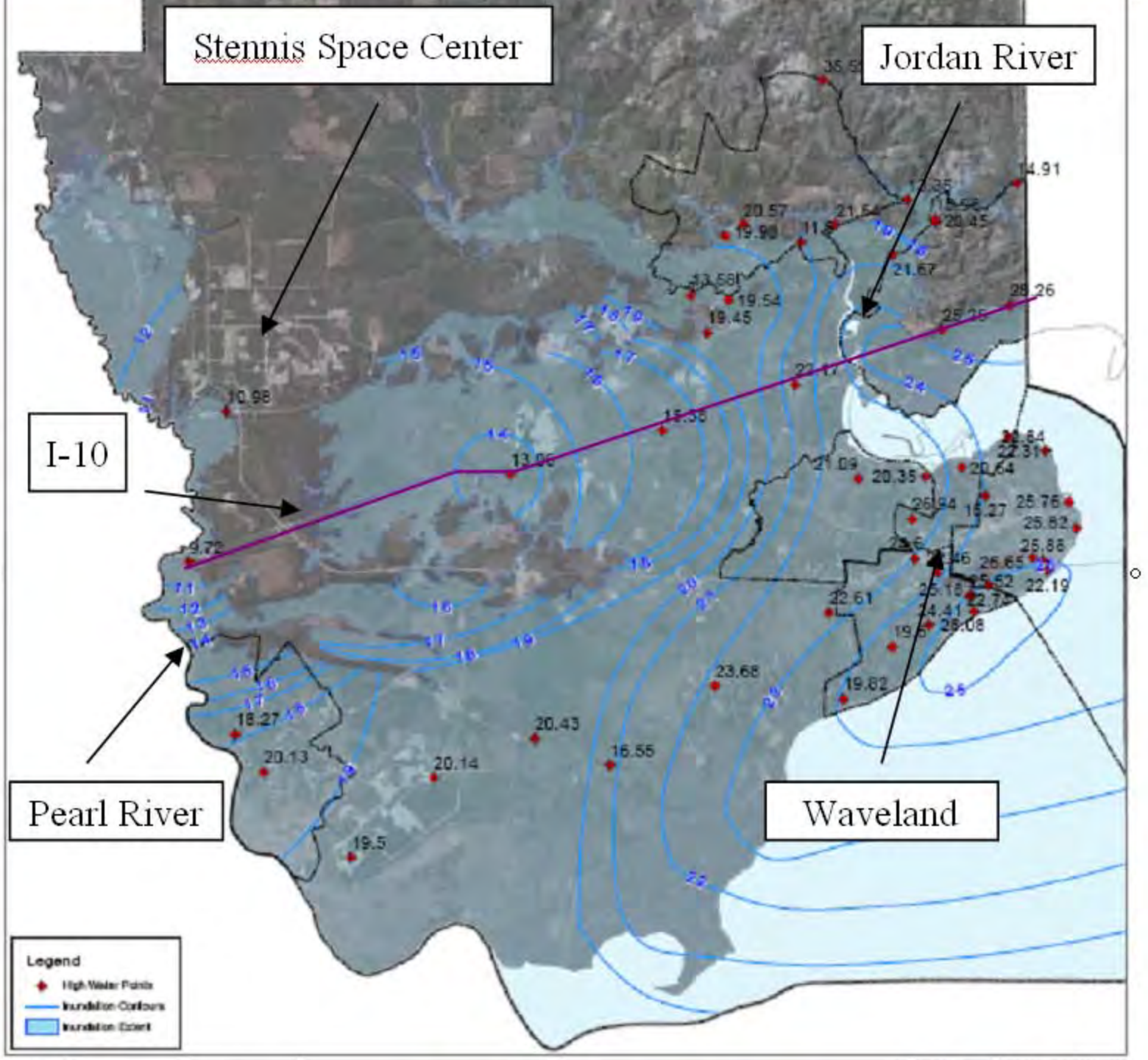
Available from four sources

- USGS tide gauges before they stopped working
- FEMA high water marks and storm surge maps
- Videos
- Storm surge simulations using Army Corps of Engineers model called ADCIRC (Advanced CIRCulation Model).

Wind and surge at tide gauge at Pearl River




H6
H7
H8
H9
H10
H11
H12
H13
G6
G7
G8
G9
G10
G11
G12
G13
F6
F7
F8
F9
F10
F11
F12
F13
E6
E7
E8
E9
E10
D6
D7
D8
C6
C8
St. Louis Bay
15
16
17
18
23
24
25

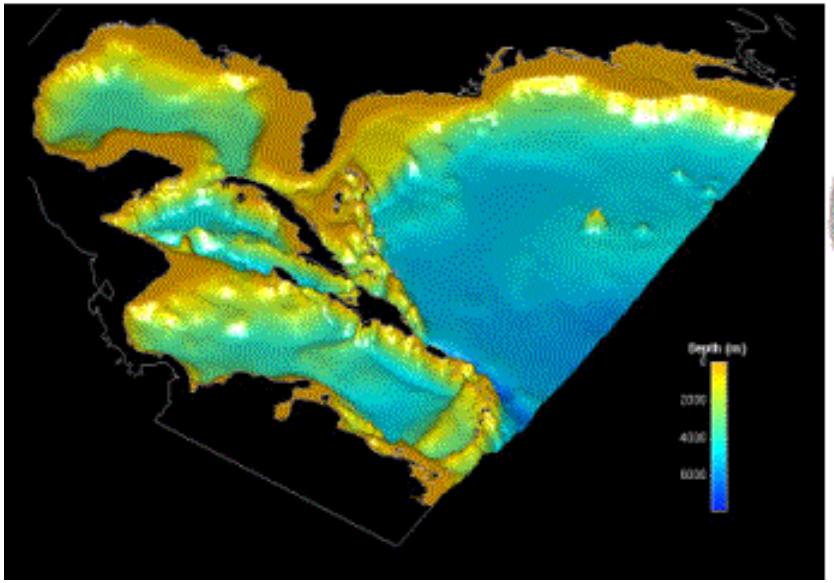

Stennis Space Center
Jordan River
I-10
Pearl River
Waveland
Legend
High Water Points
Inundation Contours
Inundation Extent

ADCIRC Storm Surge Implementation

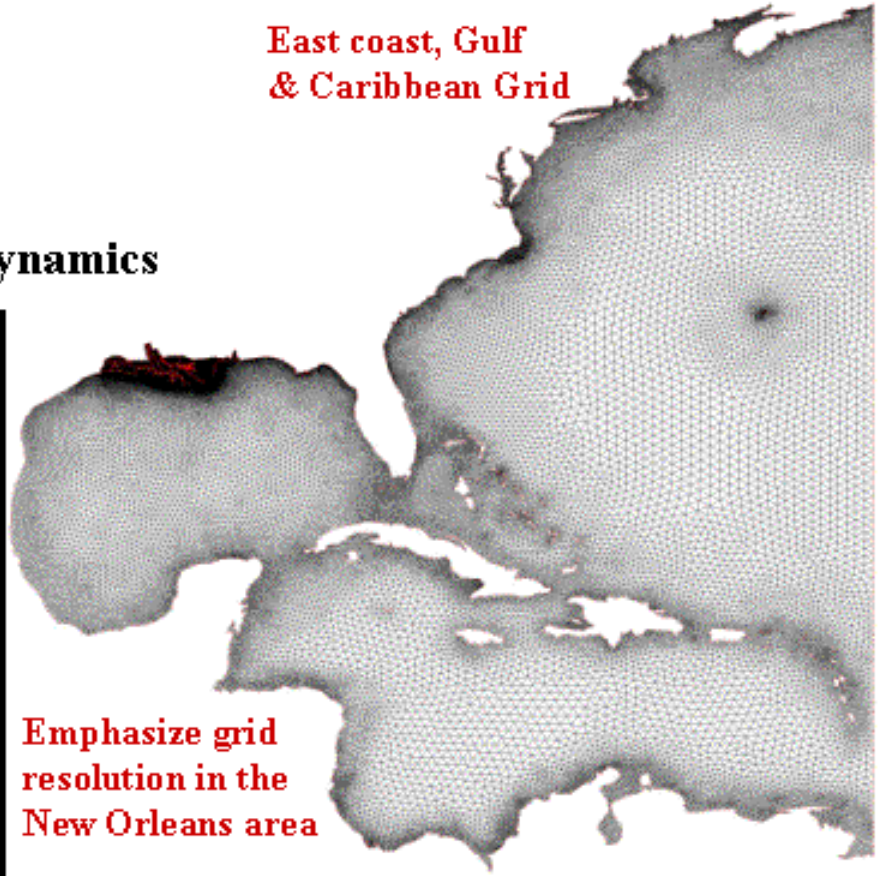
Simulation of coastal regions – Large Domain Strategy

Correctly capture

- Basin to basin interactions
- Basin to shelf dynamics
- Shelf to adjacent coast/land dynamics



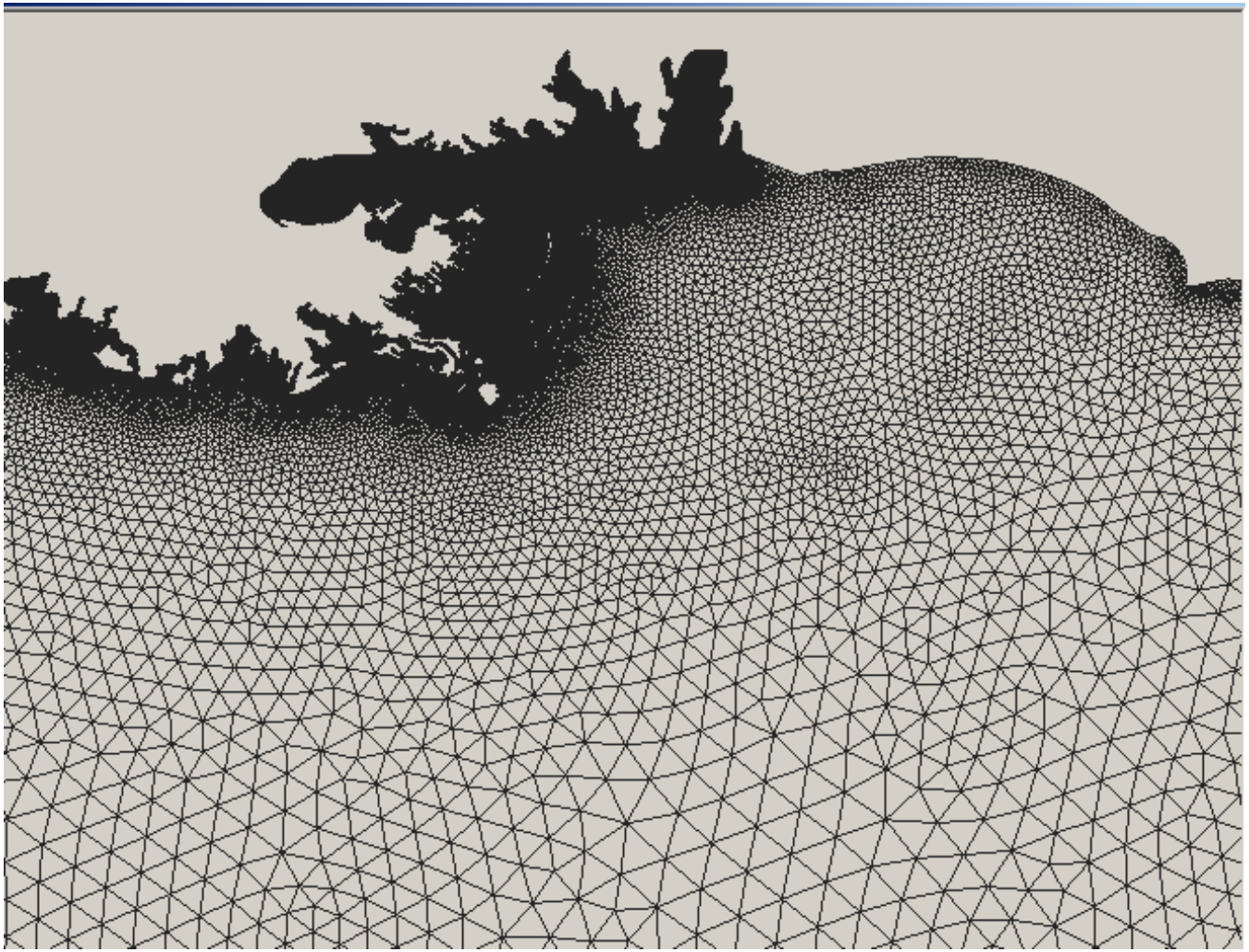
East coast, Gulf & Caribbean Grid



Emphasize grid resolution in the New Orleans area

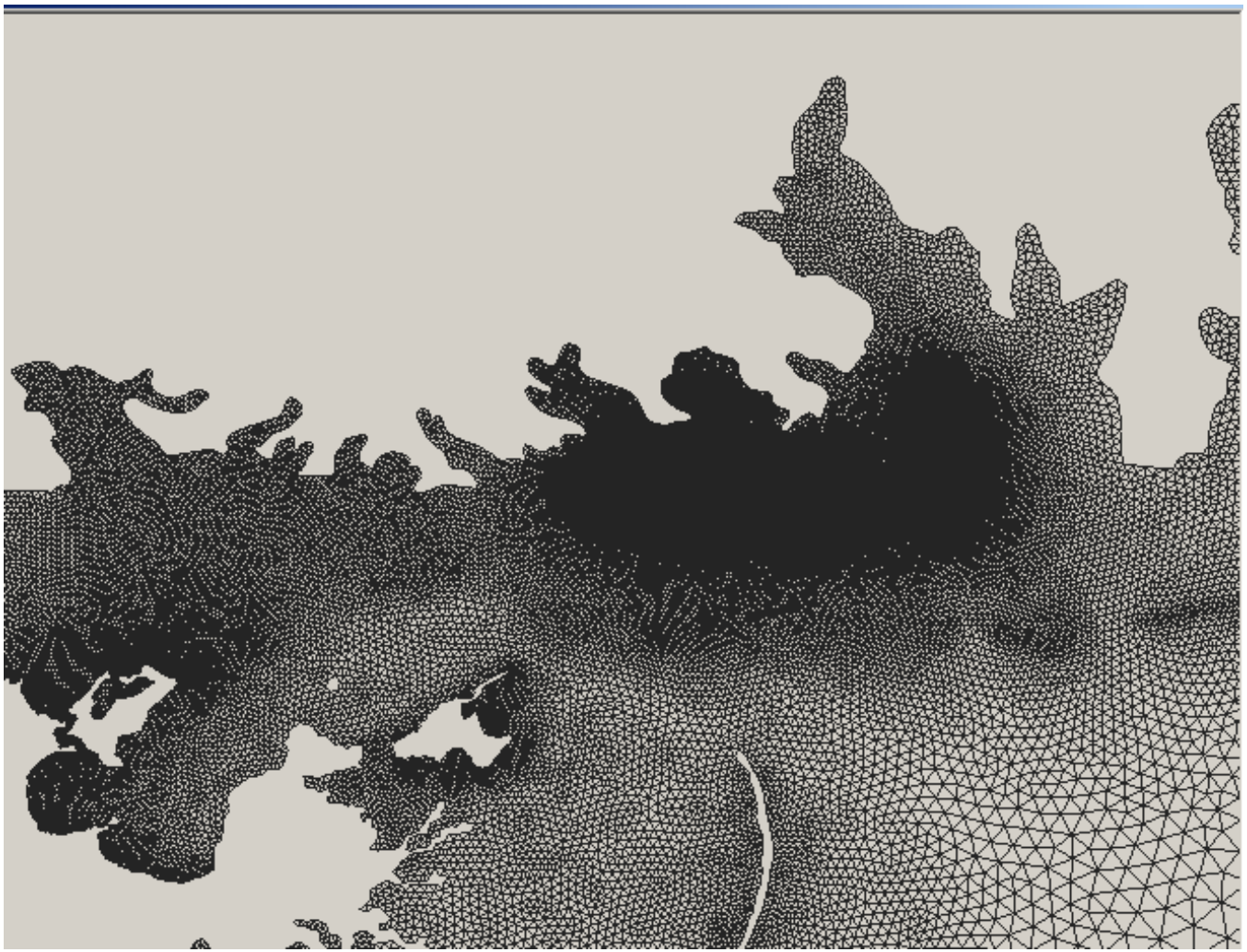
WORLDWINDS

ADCIRC grid – zoom in of North Gulf Coast



Calculations done at each point. Higher resolution done along shoreline, bays, and bayous to accurately simulation storm surge.

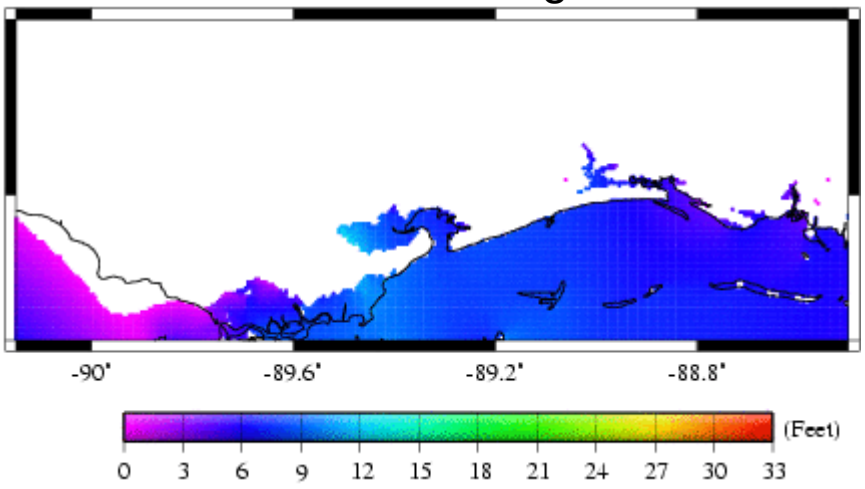
ADCIRC grid zoomed in on coastal bays and marsh



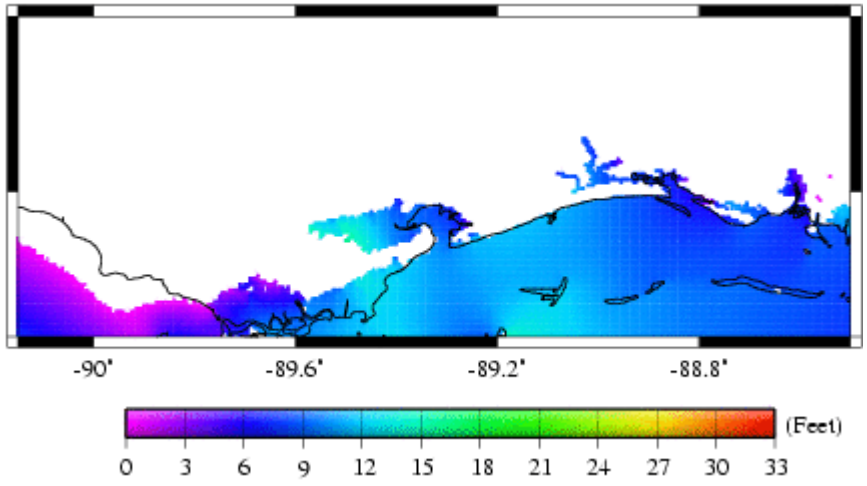
WorldWinds

ADCIRC storm surge simulation

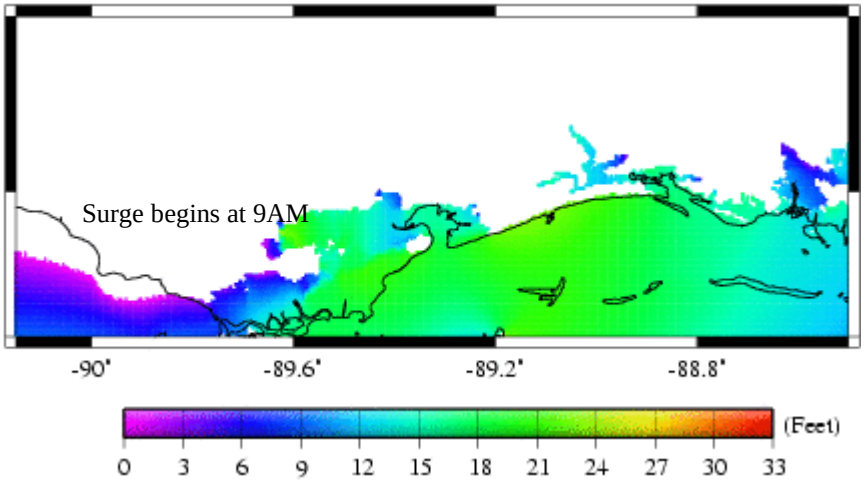
Katrina storm surge at 5AM



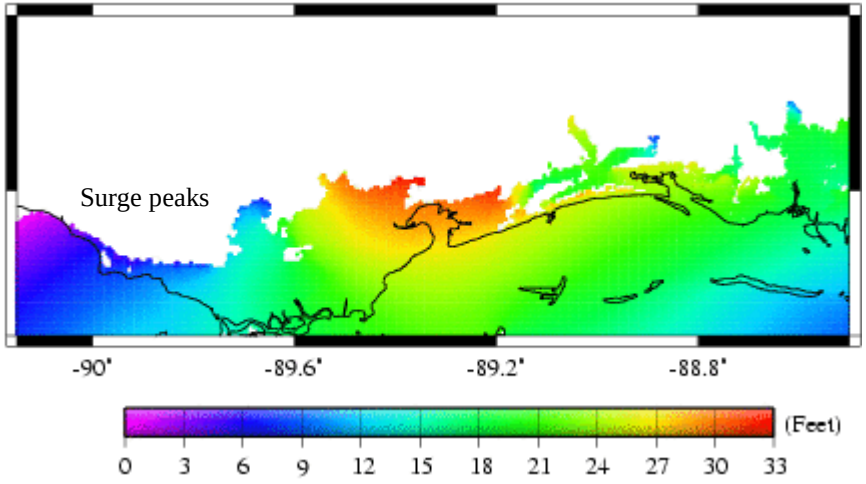
Katrina storm surge at 7AM



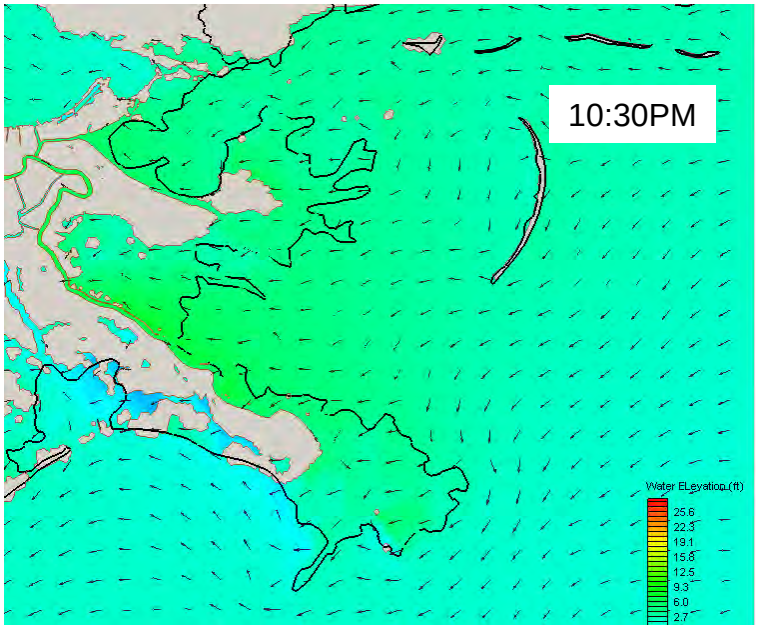
Katrina storm surge at 9AM

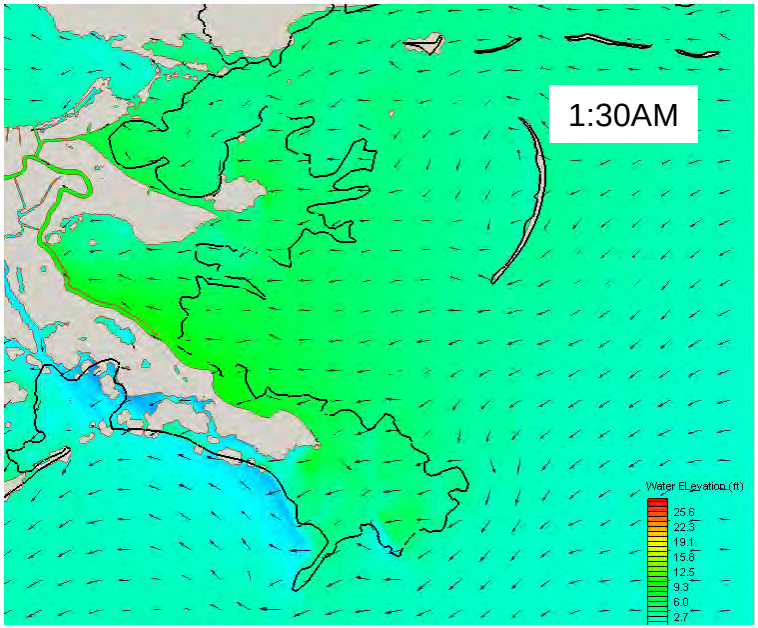


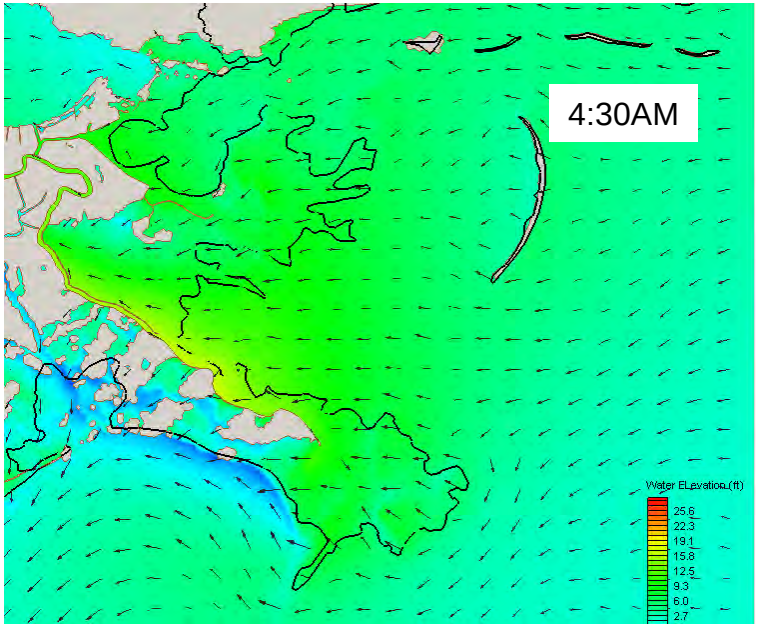
Katrina storm surge at 11AM

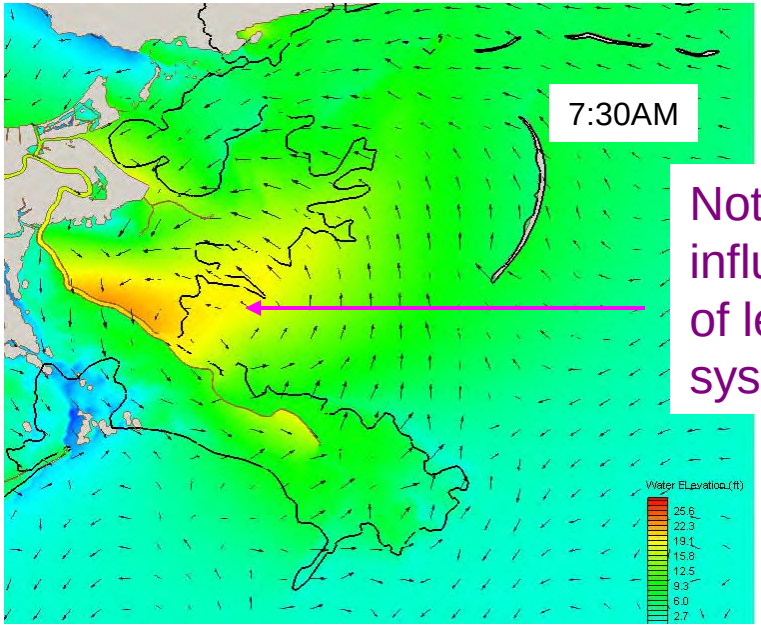


Computer simulation of Katrina storm surge in Louisiana marsh



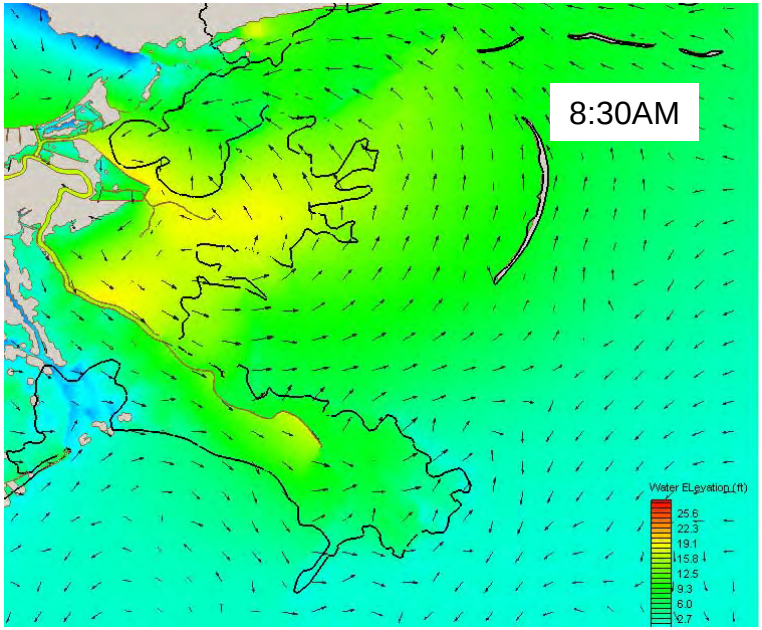


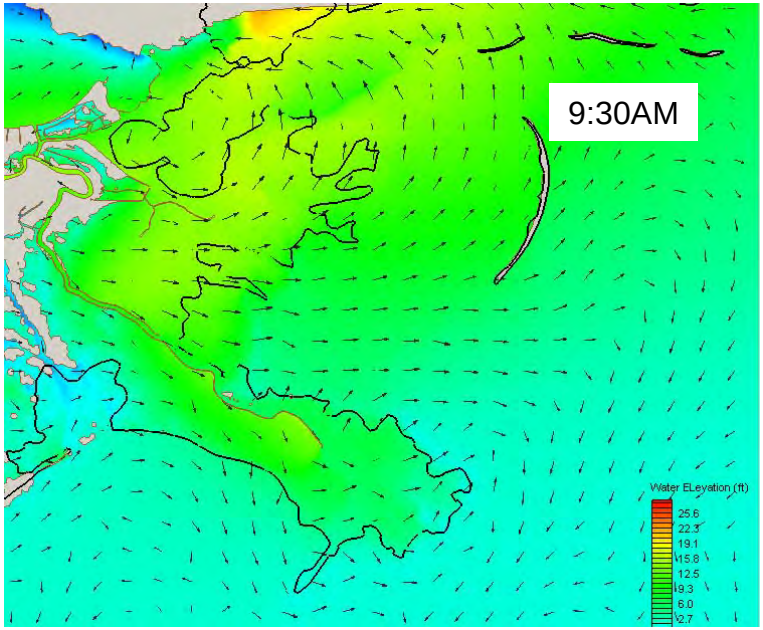


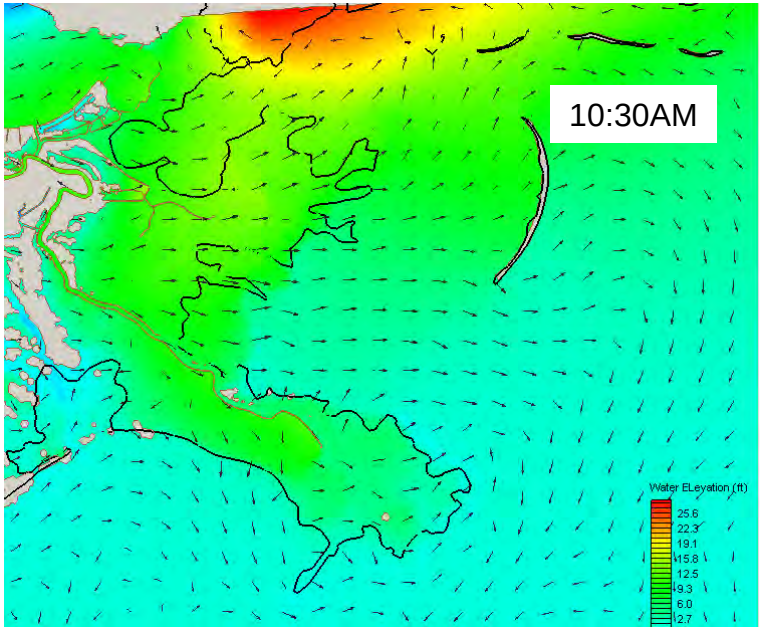


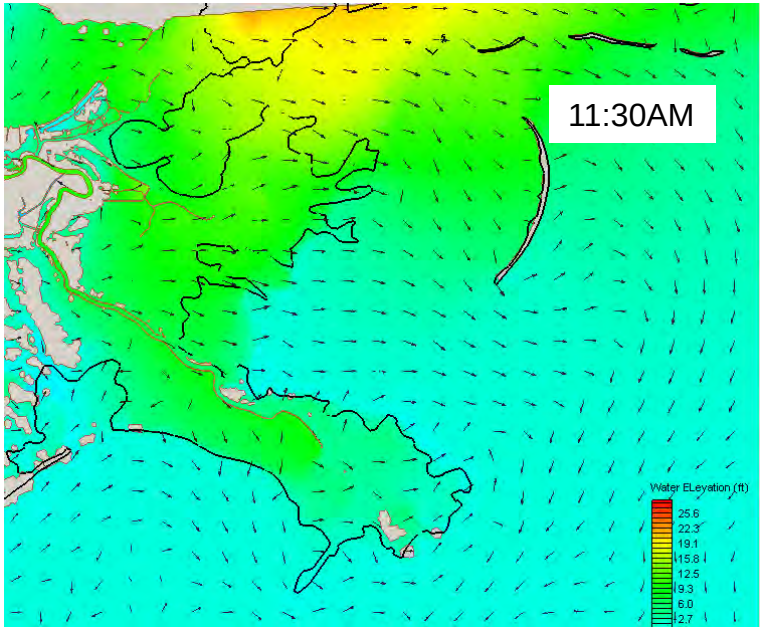
Note influence of levee system

Computer simulation of Katrina storm surge in Louisiana marsh









III. Timing of storm surge versus winds

Some tide gauge numbers

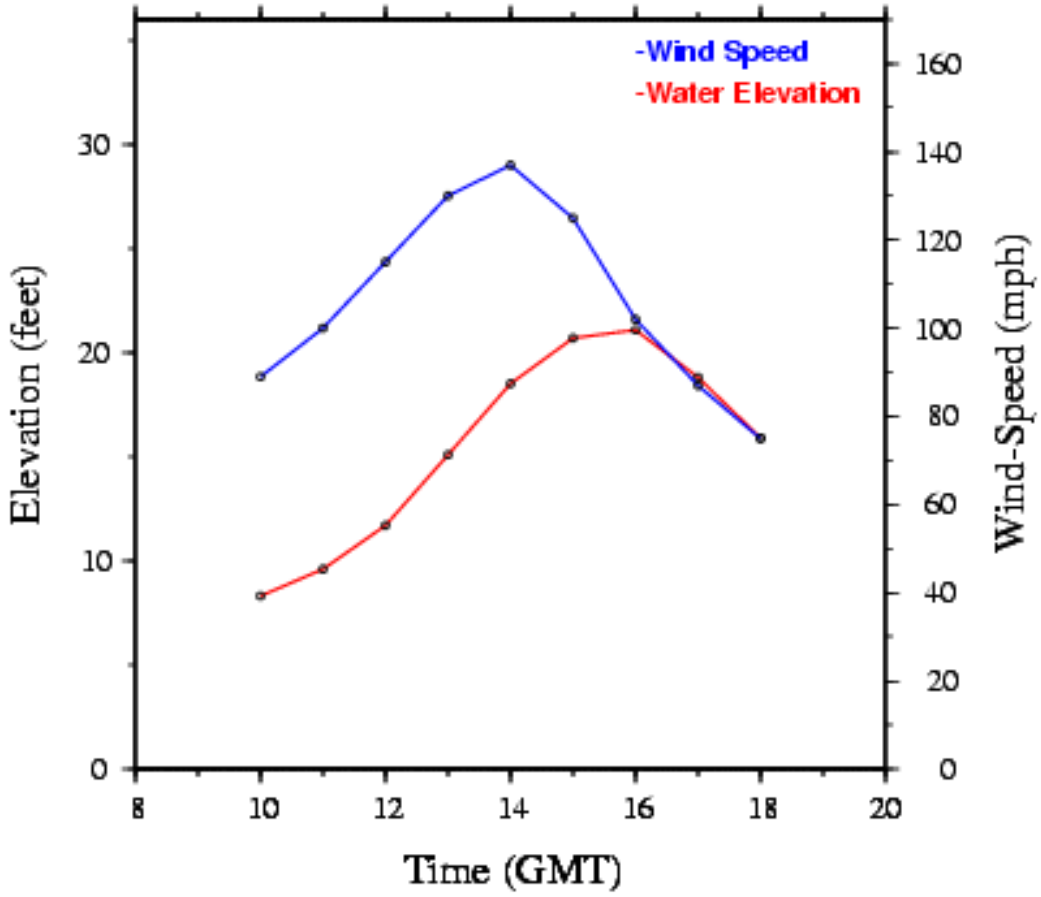
Wind (mph)	*Storm surge (feet)*	*Location*	*Time*
42	3.2	Ocean Springs	8/29 at 2:30 AM
74	8.5	Ocean Springs	8/29 at 7:15 AM
36	2.255	Mississippi Sound	8/28 at 12:00 AM
53	5.945	Mississippi Sound	8/29 at 4:00 AM
55	3.0	Pearl River	8/29 at 12:00 AM

All gauges show tropical storm-force winds approaching hurricane-force before they quit functioning. Storm surge in all cases less than 9 feet.

Hurricane Katrina (Adcirc Simulation)

TImeSeries for August 29th 10Z through 18Z

Lon=-89.190, Lat=30.185
Bay_St.Louis (East_Gulf)



Product of Mississippi State University, GeoResources Institute, Stennis Space Center.

Time series of sustained wind, wind gust, and surge in Bay St. Louis

Time (Aug. 29)	*Wind (mph)*	*Wind gust (mph)*	*Storm surge (feet)*
3:00AM	40 (east-northeast)	46	4
5:30AM	75 (east-northeast)	97	6
6:30AM	86 (northeast)	112	6
8:30AM	103 (east)	140	9
9:30AM	120 (southeast)	145	13
10:30AM	100 (south)	115	22
11:30AM	90 (west)	104	19
12:30PM	80 (west)	92	16

Numerous squall lines passed through the area after 3AM.

Tropical storm-force winds begin after midnight.
Hurricane-force winds begin around 5AM.

IV. Impact of surge on Southeast Louisiana and New Orleans

Two impacts:

1) Storm surge flooding of areas outside levees
2) Man-made disaster – flooding of New Orleans due to poorly designed levees. These levees breached.

FLASH FLOOD

urricane Katrina's Inundation f New Orleans, August 29, 2005

— By Dan Swenson, staff artist —

The day before Katr hit, high tides create by the storm's outer bands already engu low-lying wetlands a communities outside the levee system.

PLAY THE NEXT SCENE

TIME	LEGEND	CONTROL PANEL	SCENE
AM 8:00	Breach, Flooded land	Back, Next	1


leans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
GENTILLY
LAKEVIEW
MID-CITY
BYWATER
F.Q.
CARROLLTON
BROADMOOR
CBD
ALGIERS
UPTOWN
GRETNA
TERRYTOWN
MARRERO
HARVEY
Lake Borgne
POYDRAS
10
610
90
510
4:30 a.m.: Rising water in the Industrial Canal leaks through damaged gates into neighborhoods on both sides of the I-10 High Rise. The flow is minor compared to what is in store for these areas.
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
2


leans, August 29, 2005
Lake Pontchartrain
5 a.m.: Katrina's storm surge begins pounding the MR-GO levee. By dawn, levee sections crumble and Lake Borgne advances into wetlands toward St. Bernard Parish.
EASTERN NEW ORLEANS
GENTILLY
LAKEVIEW
MID-CITY
BYWATER
F.Q.
LOWER 9TH WARD
ARABI
CARROLLTON
BROADMOOR
CBD
ALGIERS
CHALMETTE
MERAUX
Mississippi River
UPTOWN
GRETNA
TERRYTOWN
ENGLISH TURN
VIOLET
MARRERO
HARVEY
POYDRAS
Lake Borgne
10
610
510
39
BUS. 90
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
3

leans, August 29, 2005

Lake Pontchartrain

VENETIAN ISLES

6:10 a.m.: Katrina makes landfall at Buras. A wall of water 21 feet high crosses the Mississippi River and its levees, inundating most of Plaquemines Parish.

EASTERN NEW ORLEANS

GENTILLY

LAKEVIEW

MID-CITY

BYWATER

F.Q.

LOWER 9TH WARD

ARABI

CARROLLTON

BROADMOOR

CBD

CHALMETTE

ALGIERS

Mississippi River

UPTOWN

GRETNA

TERRYTOWN

ENGLISH TU

MARRERO

HARVEY

POYDRAS

10 610 10 10 510 39 BUS. 90

LEGEND

Breach

Flooded land

CONTROL PANEL

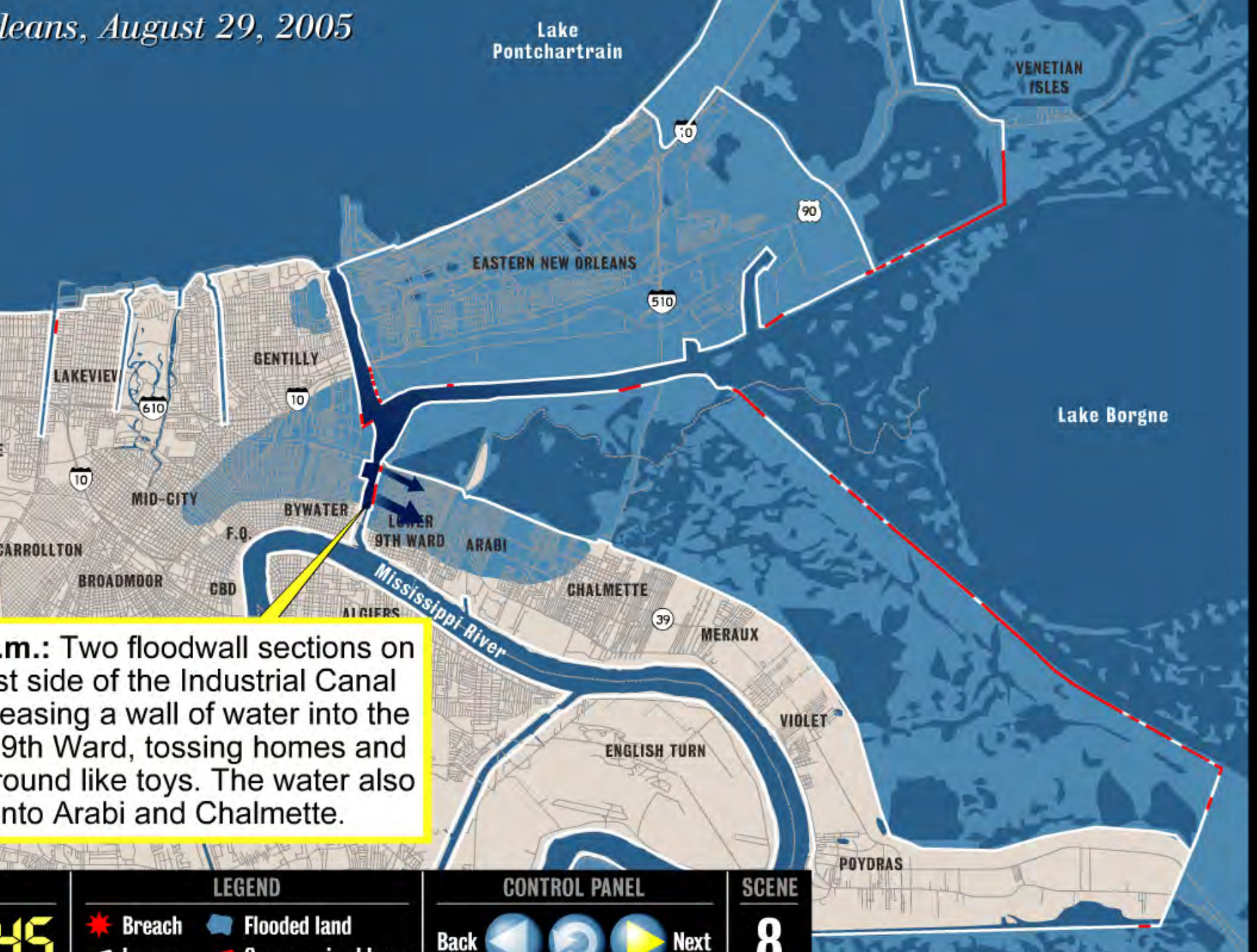
Back Next

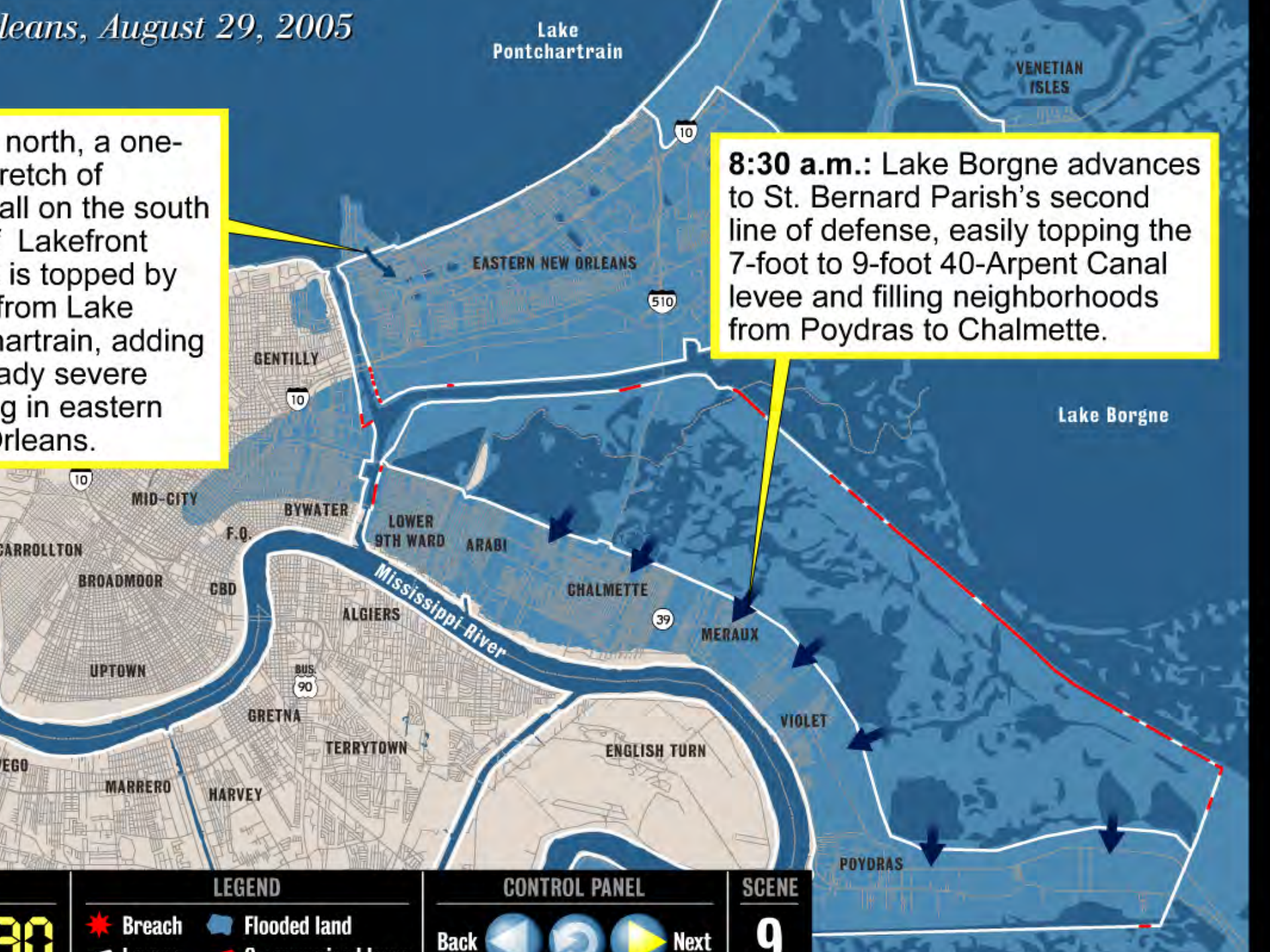
SCENE 4

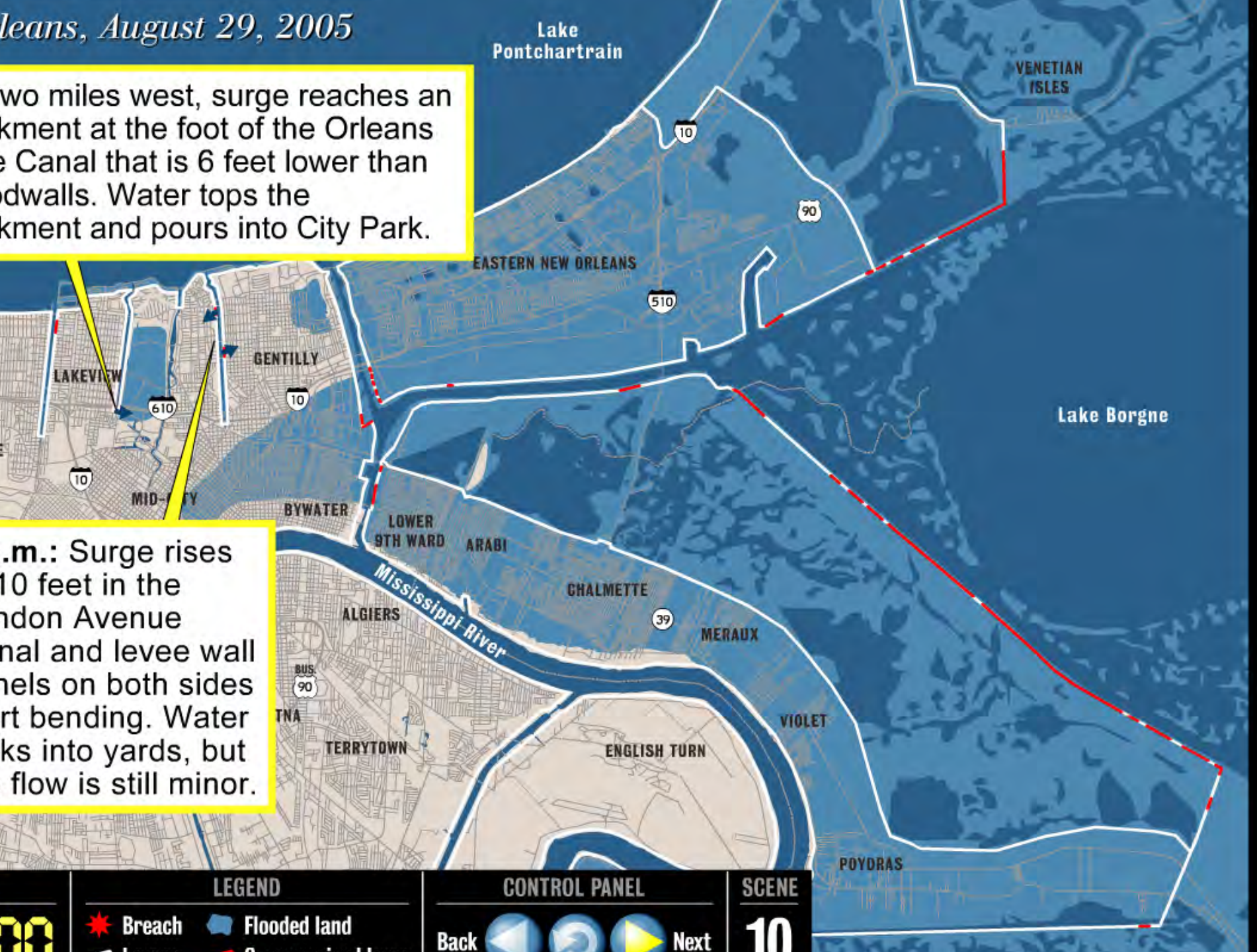

leans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
GENTILLY
LAKEVIEW
Lake Borgne
ALGIER
MARRERO
HARVEY
POYDRAS
10
610
510
90
he west, witnesses
rt sections of the 17th
et Canal levee wall are
ing toward Lakeview.
er leaks through cracks
e wall into the
hborhood.
6:30 a.m.: Surge builds in the Intracoastal Waterway's "funnel," and levees protecting eastern New Orleans are overtopped and breached. Soon, the area is under water.
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
5


leans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
6:50 a.m.: Storm surge from the "funnel" reaches the Industrial Canal. Water overtops floodwalls and levees on both sides, but the worst is still ahead.
90
GENTILLY
LAKEVIEW
610
10
Lake Borgne
10
MID-CITY
BYWATER
F.Q.
LOWER 9TH WARD
ARABI
CARROLLTON
BROADMOOR
CBD
Mississippi River
CHALMETTE
ALGIERS
39
MERAUX
UPTOWN
BUS. 90
GRETNA
VIOLET
TERRYTOWN
ENGLISH TURN
EGO
MARRERO
HARVEY
POYDRAS
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
6


leans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
7:30 a.m.: Levee wall panels on the west side of the Industrial Canal breach, flooding the Upper 9th Ward, Bywater and Treme.
90
GENTILLY
LAKEVIEW
610
10
Lake Borgne
10
MID-CITY
BYWATER
F.Q.
LOWER 9TH WARD
ARABI
CARROLLTON
BROADMOOR
CBD
Mississippi River
CHALMETTE
ALGIERS
39
MERAUX
UPTOWN
BUS. 90
GRETNA
VIOLET
TERRYTOWN
ENGLISH TURN
MARRERO
HARVEY
POYDRAS
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
7

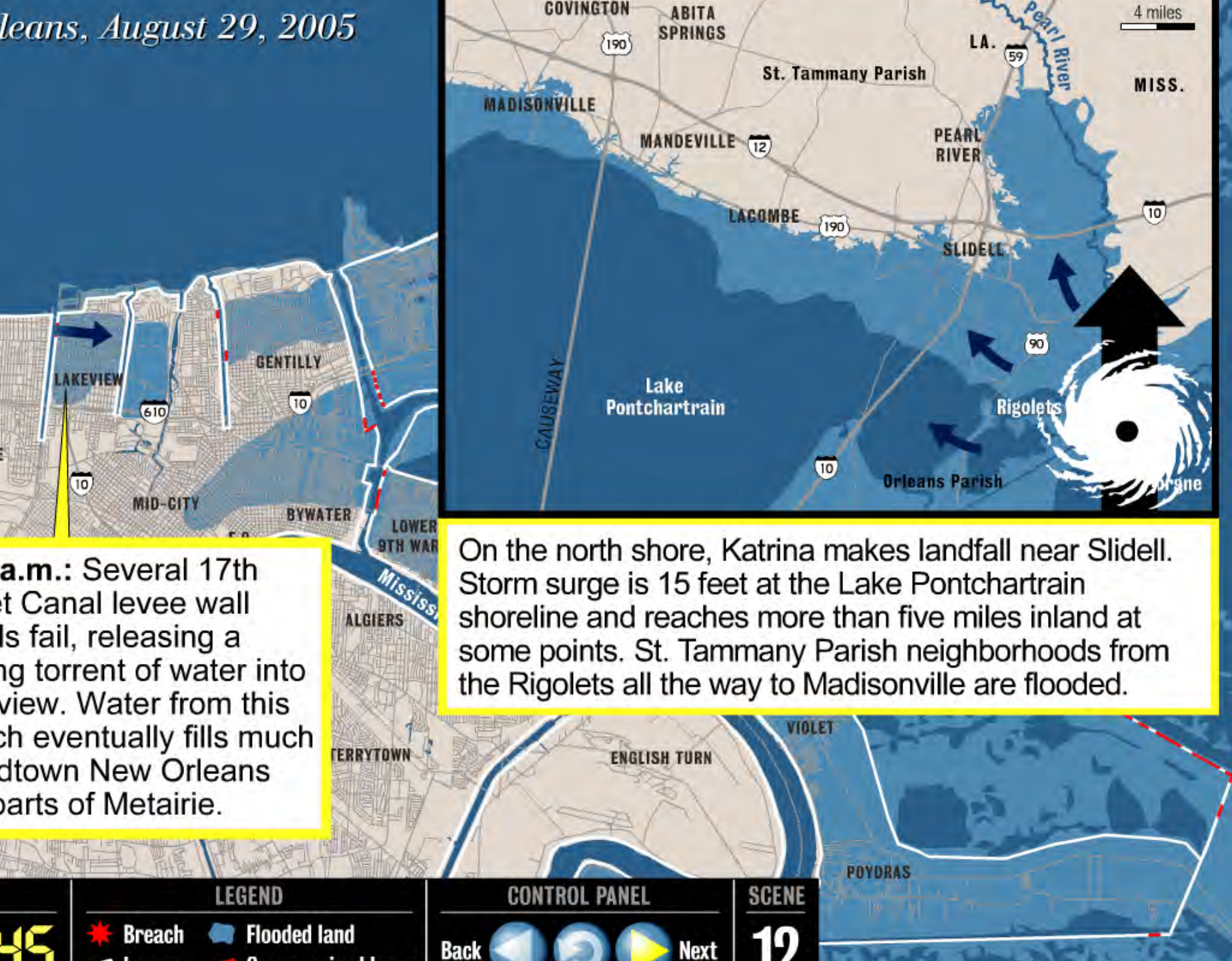

leans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
GENTILLY
LAKEVIEW
Lake Borgne
MID-CITY
BYWATER
F.Q.
9TH WARD
ARABI
CARROLLTON
BROADMOOR
CBD
CHALMETTE
MERAUX
Mississippi River
VIOLET
ENGLISH TURN
POYDRAS
.m.: Two floodwall sections on
st side of the Industrial Canal
easing a wall of water into the
9th Ward, tossing homes and
round like toys. The water also
nto Arabi and Chalmette.
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
8


leans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
north, a one-
retch of
all on the south
Lakefront
is topped by
from Lake
hartrain, adding
ady severe
g in eastern
rleans.
8:30 a.m.: Lake Borgne advances to St. Bernard Parish's second line of defense, easily topping the 7-foot to 9-foot 40-Arpent Canal levee and filling neighborhoods from Poydras to Chalmette.
EASTERN NEW ORLEANS
GENTILLY
Lake Borgne
MID-CITY
BYWATER
F.Q.
LOWER 9TH WARD
ARABI
CARROLLTON
BROADMOOR
CBD
CHALMETTE
Mississippi River
ALGIERS
MERAUX
UPTOWN
GRETNA
TERRYTOWN
ENGLISH TURN
VIOLET
MARRERO
HARVEY
POYDRAS
10
510
39
90
BUS
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
9


leans, August 29, 2005
wo miles west, surge reaches an
kment at the foot of the Orleans
e Canal that is 6 feet lower than
odwalls. Water tops the
kment and pours into City Park.
.m.: Surge rises
10 feet in the
ndon Avenue
nal and levee wall
nels on both sides
rt bending. Water
ks into yards, but
flow is still minor.
Lake
Pontchartrain
VENETIAN
ISLES
EASTERN NEW ORLEANS
GENTILLY
LAKEVIEW
MID-CITY
BYWATER
LOWER
9TH WARD
ARABI
CHALMETTE
ALGIERS
Mississippi River
MERAUX
TNA
TERRYTOWN
ENGLISH TURN
VIOLET
POYDRAS
Lake Borgne
10
90
510
610
39
BUS.
90
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
10


leans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
GENTILLY
LAKEVIEW
Lake Borgne
BYWATER
LOWER 9TH WARD
ARABI
F.Q.
CBD
ALGIERS
CHALMETTE
MERAUX
Mississippi River
GRETNA
TERRYTOWN
HARVEY
ENGLISH TURN
VIOLET
POYDRAS
10
90
510
610
39
BUS. 90
a.m.: l-wall
s on the east
f the London
ue Canal fail,
sing a wall of
and sand
omes and
nding the
ng of Gentilly.
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
11

leans, August 29, 2005



a.m.: Several 17th
t Canal levee wall
ls fail, releasing a
ng torrent of water into
view. Water from this
ch eventually fills much
dtown New Orleans
arts of Metairie.

On the north shore, Katrina makes landfall near Slidell. Storm surge is 15 feet at the Lake Pontchartrain shoreline and reaches more than five miles inland at some points. St. Tammany Parish neighborhoods from the Rigolets all the way to Madisonville are flooded.

LEGEND

Breach

Flooded land

CONTROL PANEL

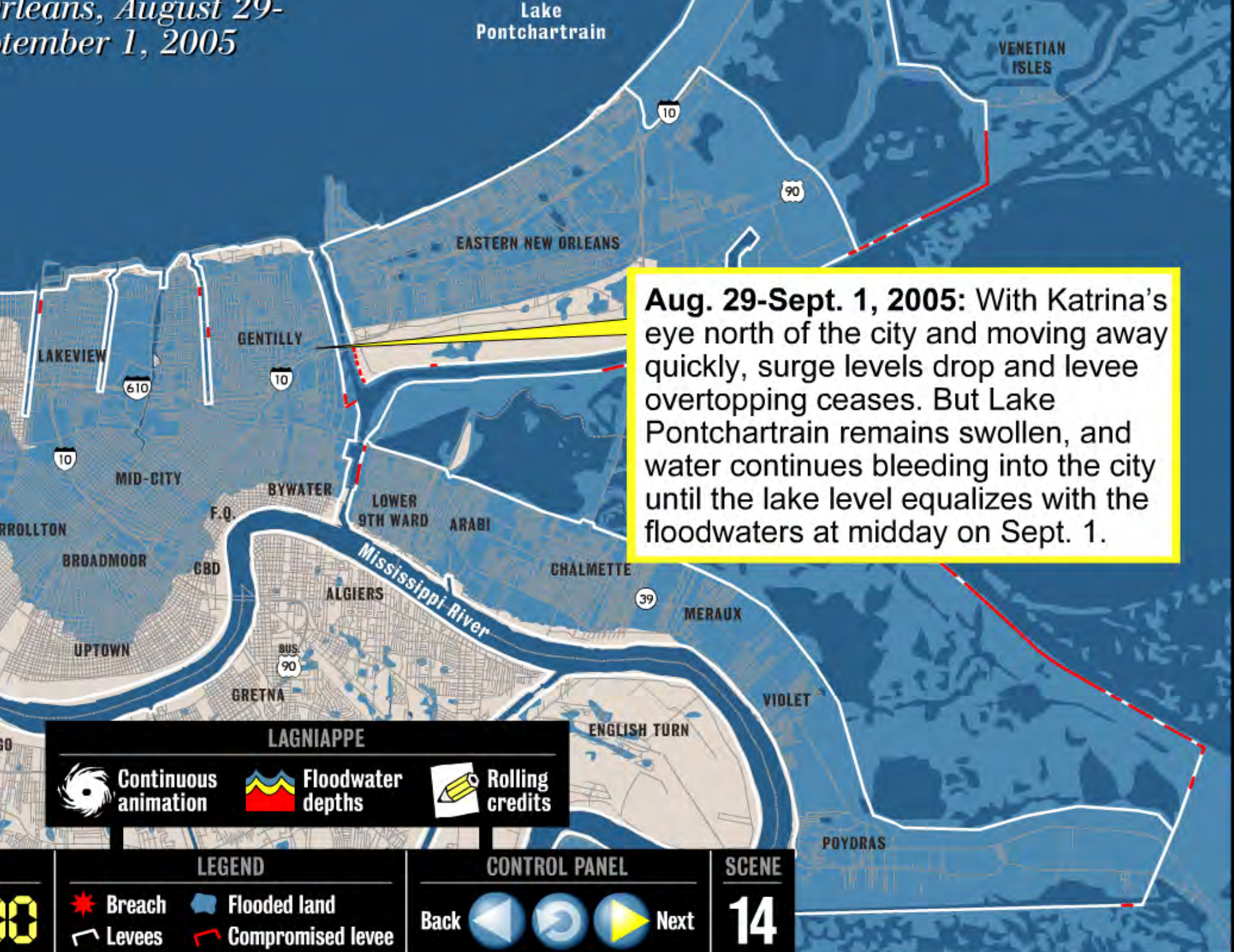
Back

Next

SCENE

12


leans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
10:30 a.m.: I-wall panels on the west side of the London Avenue Canal are pushed over, adding 8 feet of water to flooded Gentilly and contributing to rising water across the city.
90
GENTILLY
LAKEVIEW
610
10
Lake Borgne
10
MID-CITY
BYWATER
F.Q.
LOWER 9TH WARD
ARABI
CBD
CHALMETTE
Mississippi River
ALGIERS
39
MERAUX
BUS
90
GRETNA
VIOLET
TERRYTOWN
ENGLISH TURN
HARVEY
POYDRAS
of
on
also
s
ter
hrough
taffed
ng
.
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
13


rleans, August 29-
tember 1, 2005
Lake
Pontchartrain
VENETIAN
ISLES
10
90
EASTERN NEW ORLEANS
Aug. 29-Sept. 1, 2005: With Katrina's eye north of the city and moving away quickly, surge levels drop and levee overtopping ceases. But Lake Pontchartrain remains swollen, and water continues bleeding into the city until the lake level equalizes with the floodwaters at midday on Sept. 1.
GENTILLY
LAKEVIEW
610
10
10
MID-CITY
BYWATER
F.Q.
LOWER
9TH WARD
ARABI
RROLLTON
BROADMOOR
CBD
Mississippi River
CHALMETTE
39
MERAUX
ALGIERS
UPTOWN
BUS.
90
GRETNA
VIOLET
ENGLISH TURN
POYDRAS
LAGNIAPPE
Continuous animation
Floodwater depths
Rolling credits
LEGEND
Breach
Flooded land
Levees
Compromised levee
CONTROL PANEL
Back
Next
SCENE
14

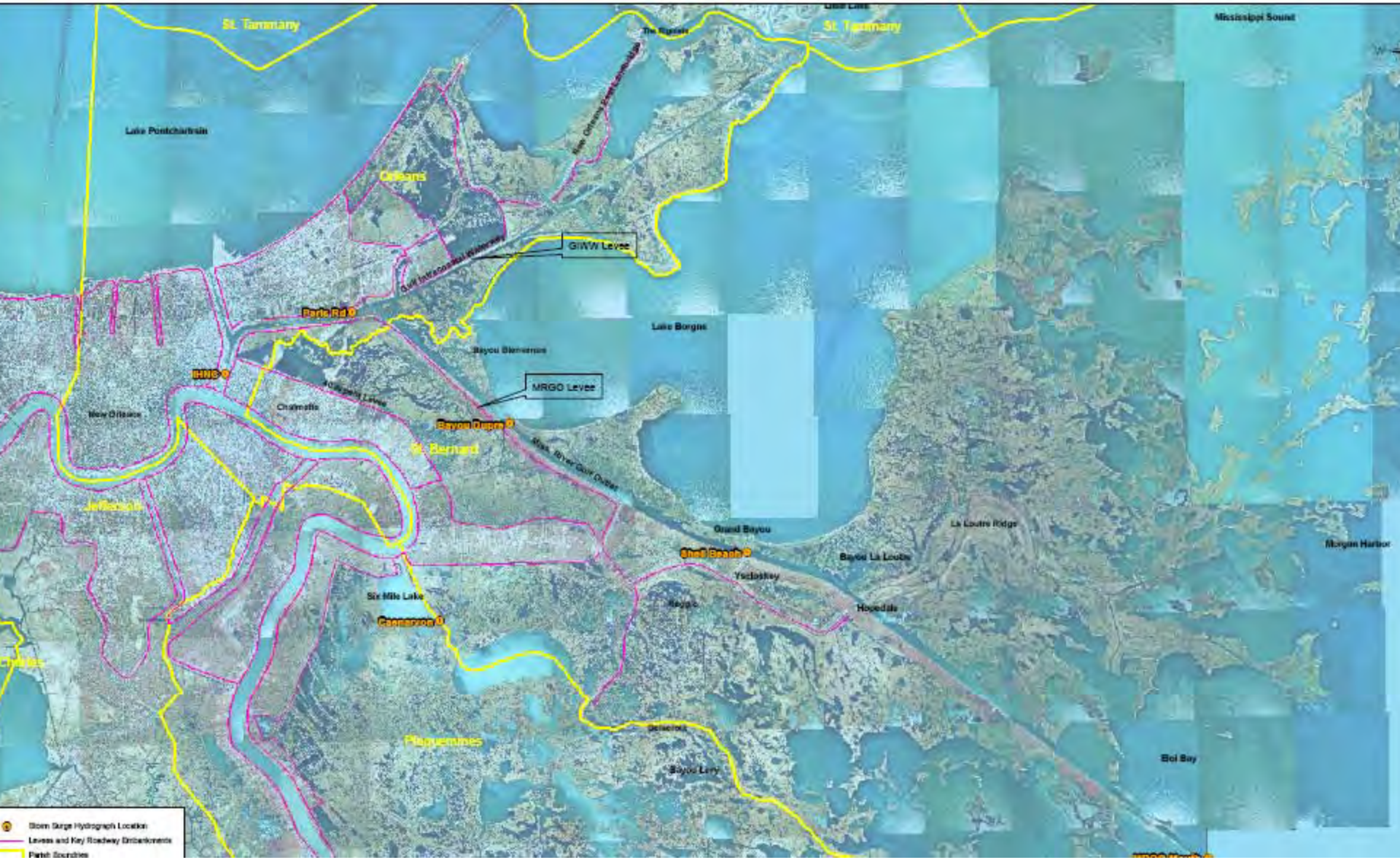
V. Influence of the Mississippi River Gulf Outlet (MRGO), and the Intercoastal Waterway

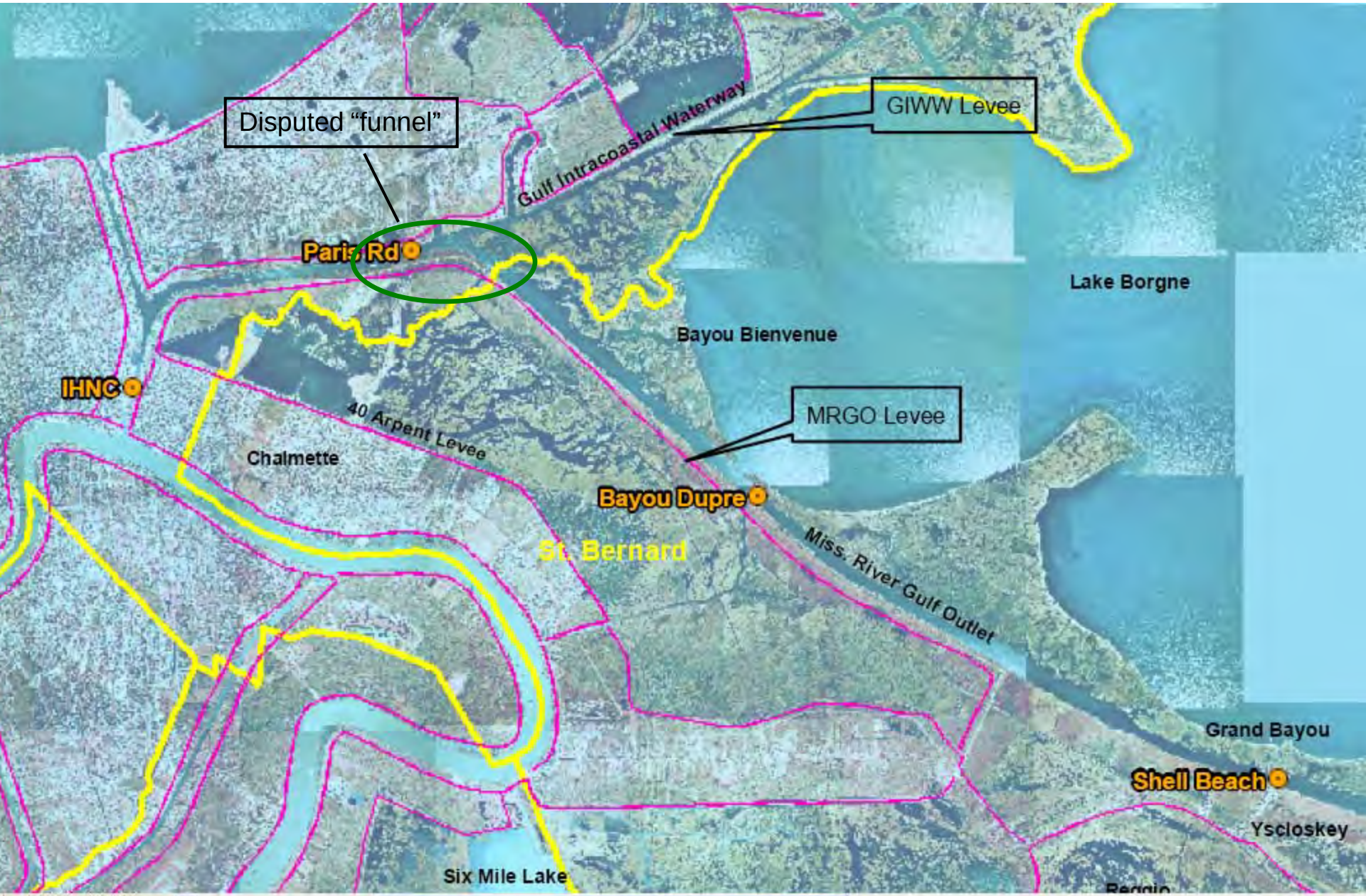
- Is MRGO a “storm surge” highway?
- Is the confluence of these two waterways a dangerous “funnel”?

Mississippi River Gulf Outlet (MRGO)

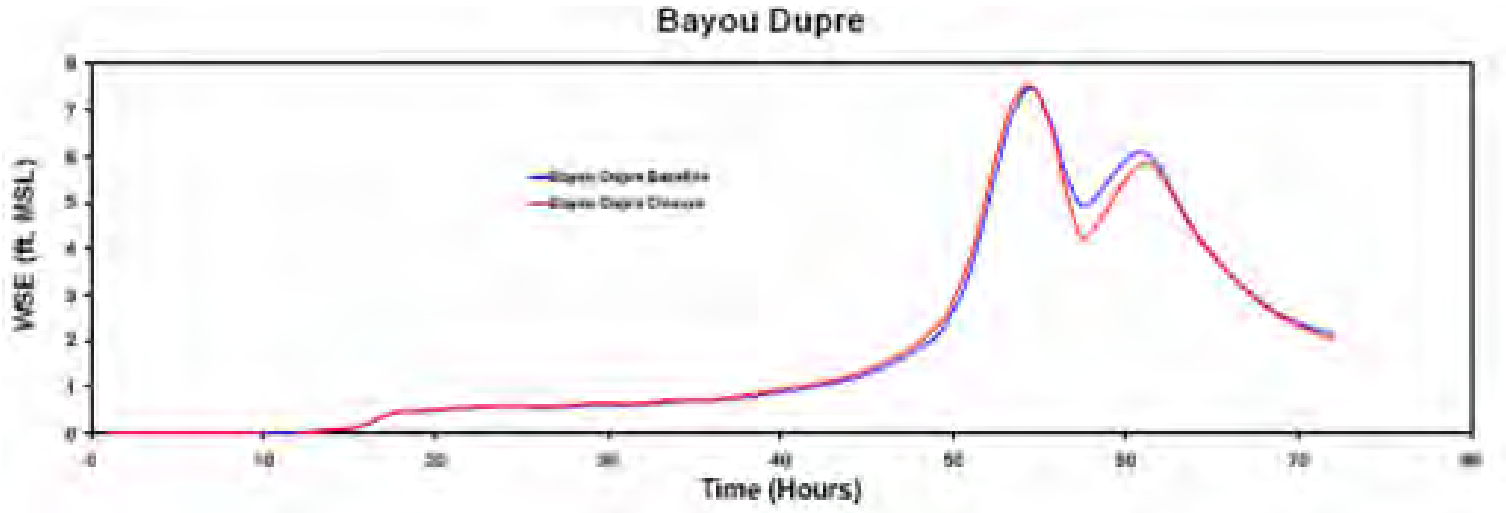
- A 70-mile, deep-draft, man-made channel, completed in 1963
- 40 miles was dredged through marshland in St. Bernard Parish
- Originally 750 feet wide, has eroded to 2000 feet wide in many places
- Destroyed more than 36,000 acres of wetlands
- Has disrupted a brackish, lush environment with high salinity.

New Orleans and eastern marsh system



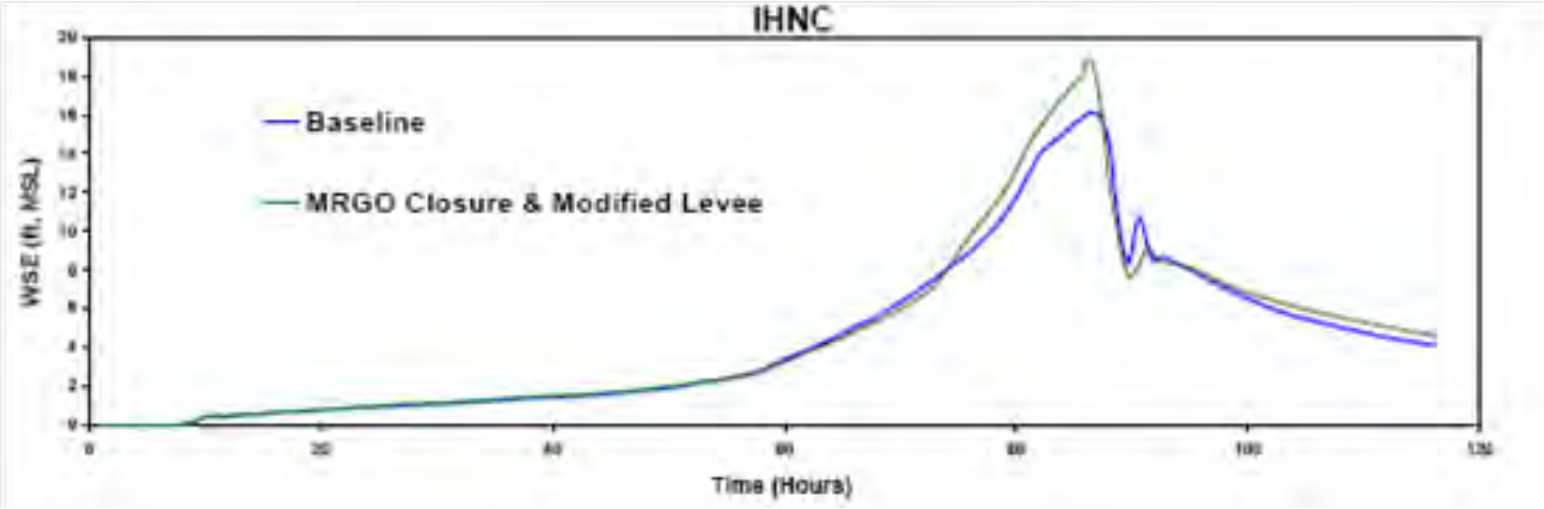

Disputed "funnel"
GIWW Levee
Gulf Intracoastal Waterway
Paris Rd
Lake Borgne
Bayou Bienvenue
IHNC
40 Arpent Levee
MRGO Levee
Chalmette
Bayou Dupre
St. Bernard
Miss. River Gulf Outlet
Grand Bayou
Shell Beach
Yscloskey
Six Mile Lake

ADCIRC simulations with MRGO open (blue) and closed (red)



Little impact of the MRGO on the storm surge at Bayou Dupre south of Lake Borgne. This result is typical throughout the region.

ADCIRC simulations with MRGO open (blue) and wider levee system along canals (green)



A wider levee system actually yields higher surge elevations, because the conveyance increases. The "funneling effect" may not occur as theorized and requires more research.

However, the "funnel" region may have stressed the levees, and requires a separate engineering study.

Conclusions

- Katrina's record storm surge in Mississippi due to size of storm, Category 3 intensity, shallow bathymetry, and Mississippi River levee forcing. Inundation occurred from Fourchon, LA (west of the Mississippi River) to coastal Alabama, with inland flooding miles inland for some locations (Bay St. Louis, Slidell).

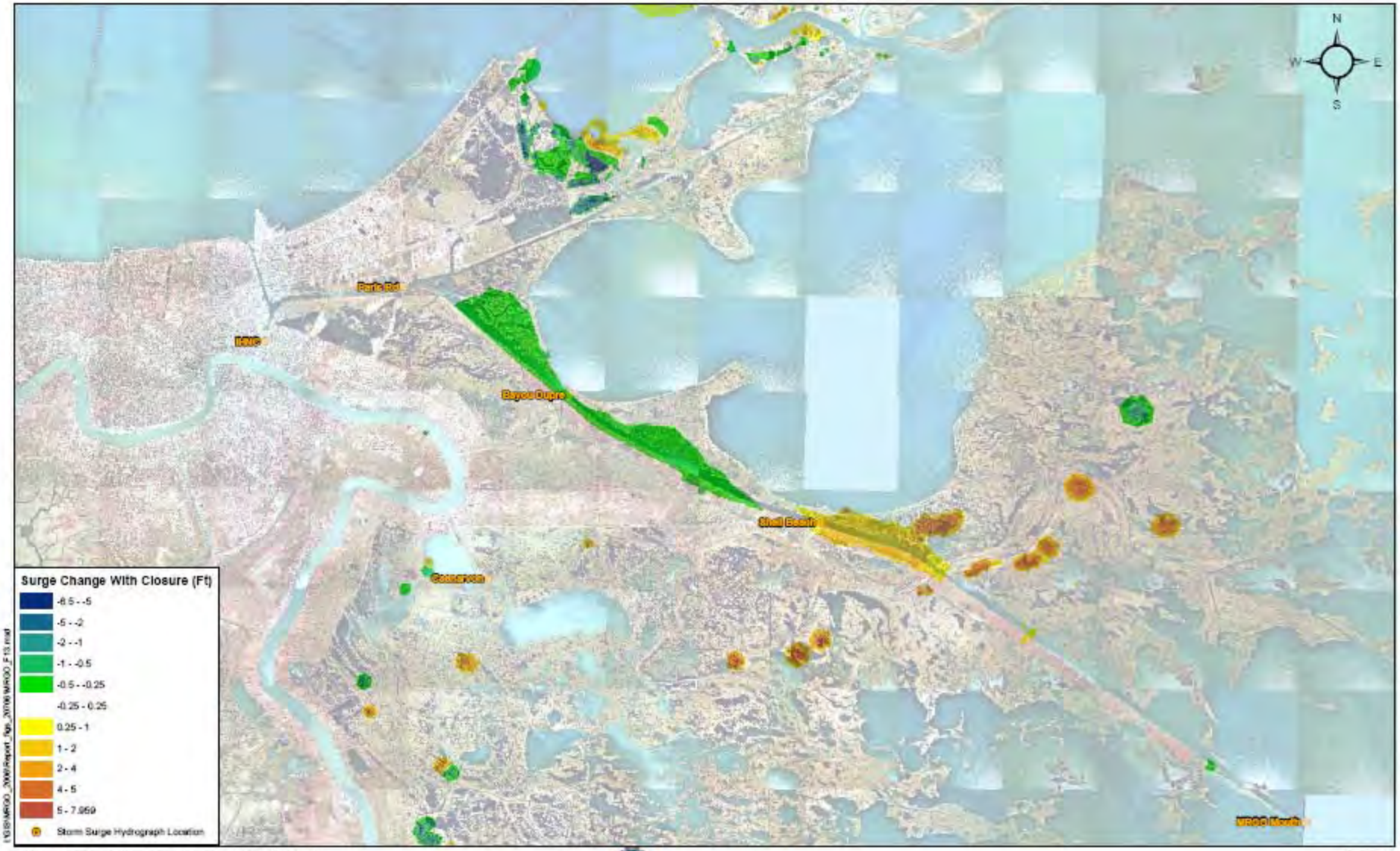
- The ADCIRC model, eyewitness accounts, tide gauge data, and video show hurricane-force winds occurred three to four hours many homes had inundation. Tropical storm-force winds began 9 hours before the major surge impact. For example, the peak surge occurred between 8:30AM and 11AM in Bay St. Louis. Hurricane-force winds started at 5AM, and tropical storm-force winds started at midnight in Bay St. Louis.

- Along the northshore of Lake Pontchartrain, the surge was delayed due to a "sloshing effect" in Lake Pontchartrain related to a north-south wind direction shift as Katrina moved inland.

- It's important to remember that much of the devastation in New Orleans was due to shoddy levees (built by the Corps of Engineers) which failed.

- MRGO probably contributed little to the Louisiana surge. This is a reasonable conclusion, since the whole wetlands were underwater, making MRGO a non-factor. The surge also was a 50-mile wide event, making the MRGO comparatively insignificant. *However, because MRGO is an ecological disaster, and due to extreme damage in eastern New Orleans and St. Bernard Parish, it is very difficult to convince anyone in Louisiana of these results.*

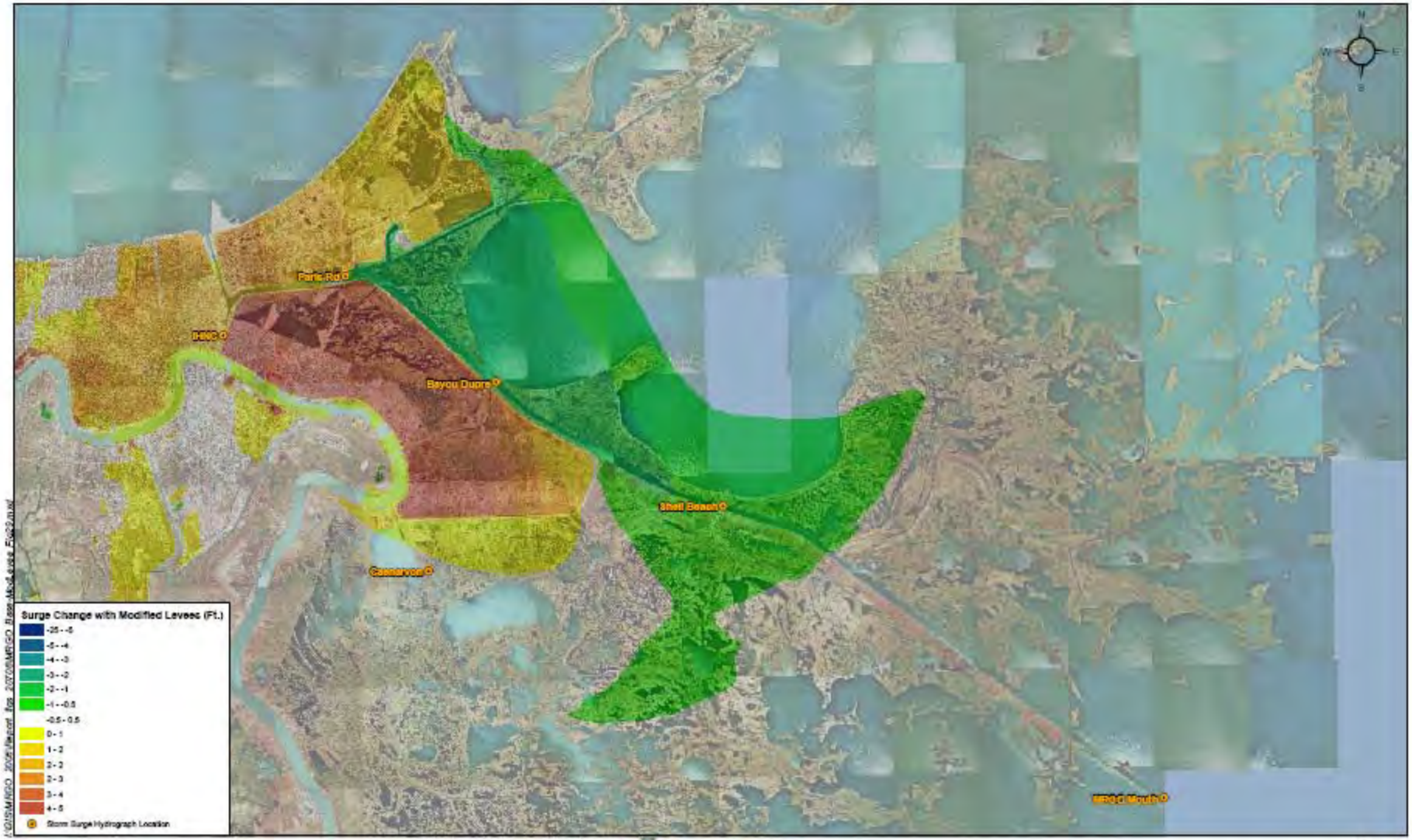
- The MRGO-Intercoastal "funnel" may have complicated, counterintuitive physics. Widening the levee system could actually increase storm surge conveyance.



NOTE: Surge Reduction with Closure is Negative (Green).
Surge Increase with Closure is Positive (Red).

URS

Figure 13
Difference in Maximum Water Surface Elevation for 124-Knot-Fast Storm, Baseline vs. Closed MRGO



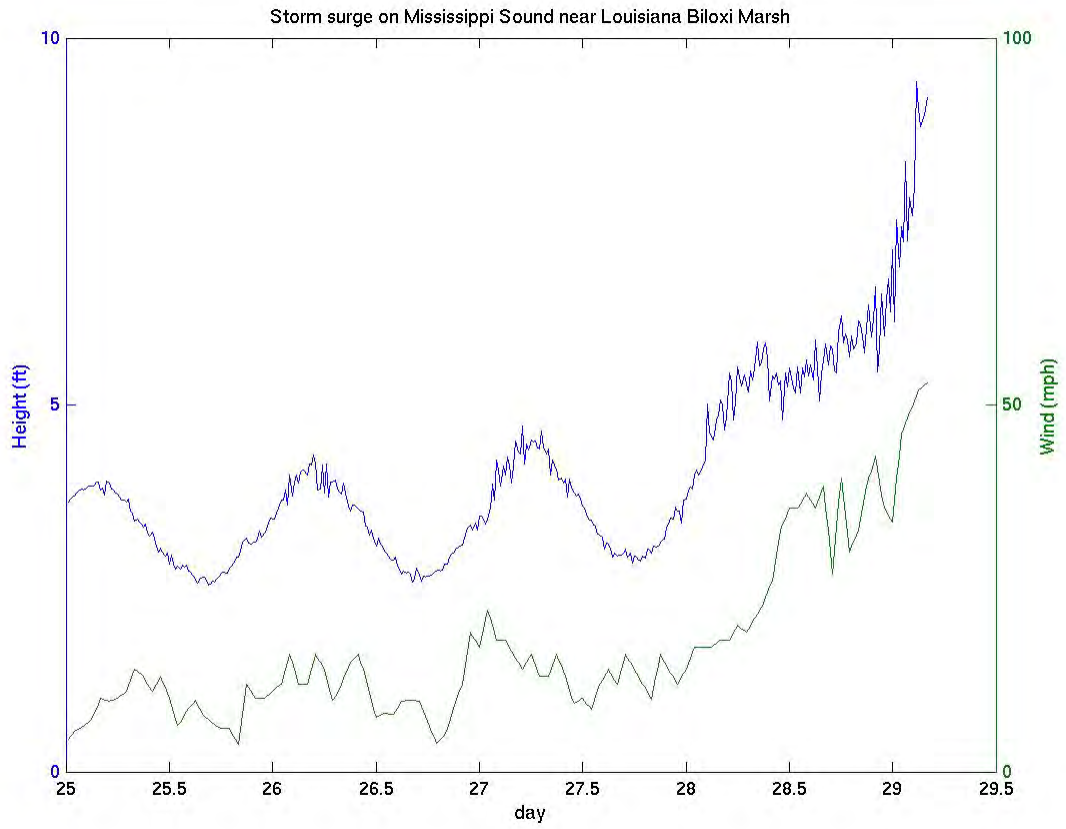
NOTE: Surge Reduction with Modification is Negative (Green).
Surge Increase with Modification is Positive (Red).

0 10,000 20,000 40,000 Feet

URS

Figure 29
Difference in Maximum Water Surface Elevation for Hurricane Katrina, Baseline vs. Modified Levees MRGO

Wind and surge at tide gauge in Mississippi Sound



Wind and surge at tide gauge at Ocean Springs