# Improvements to Southeast Louisiana's floodwalls and pump stations since Katrina: the Hurricane and Storm Damage Risk Reduction System (HSDRRS)

Pat Fitzpatrick
Mississippi State University

- Review of levee failure during Katrina
- Overview of HSDRRS
- Overview of Joint Probability Methods (JPM) used in hazard risk assessment
- JPM application to determining 100-year flood levels for HSDRRS
- HSDRRS concerns

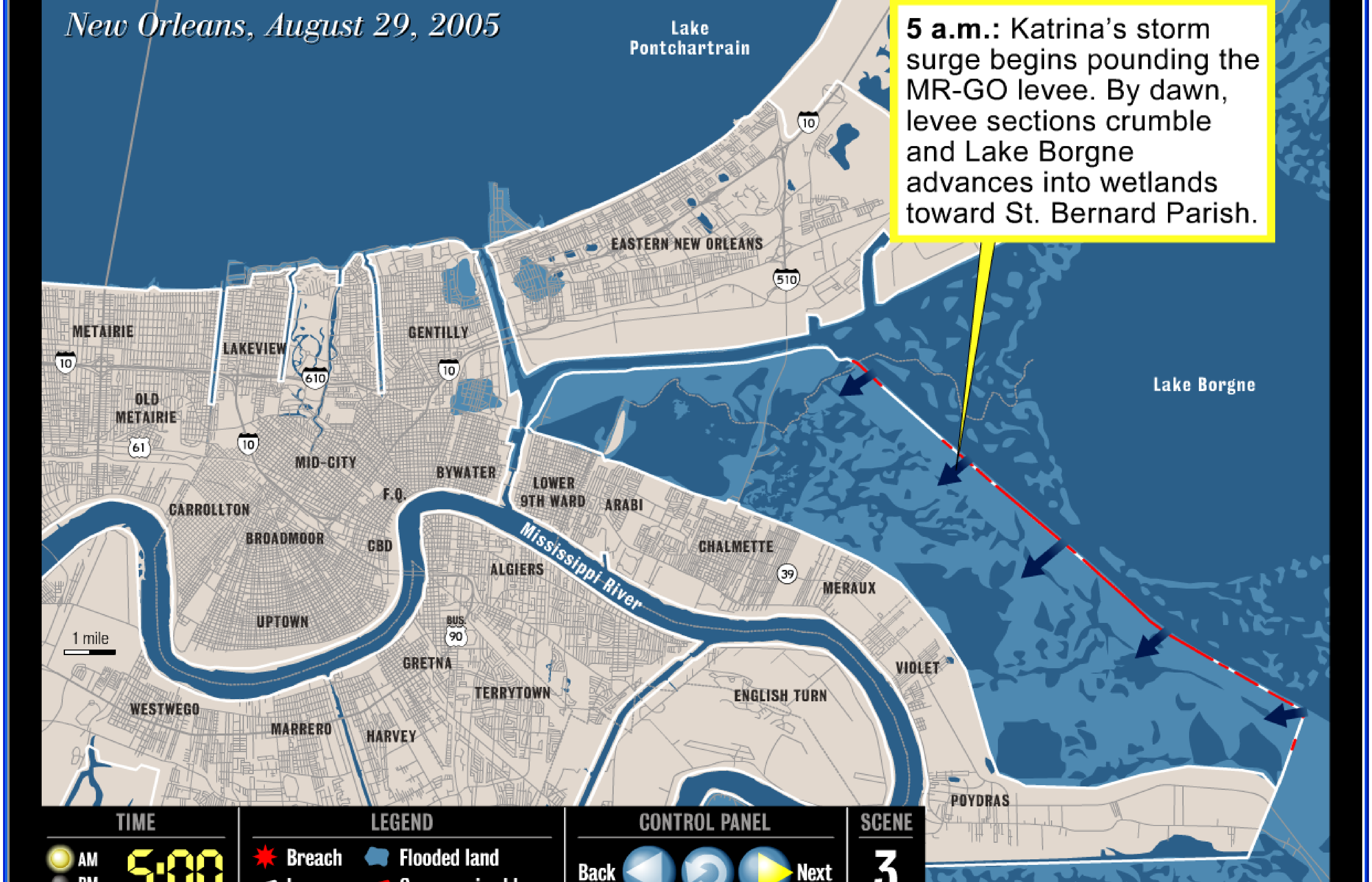
# Levee failure timetable
# Hurricane Katrina

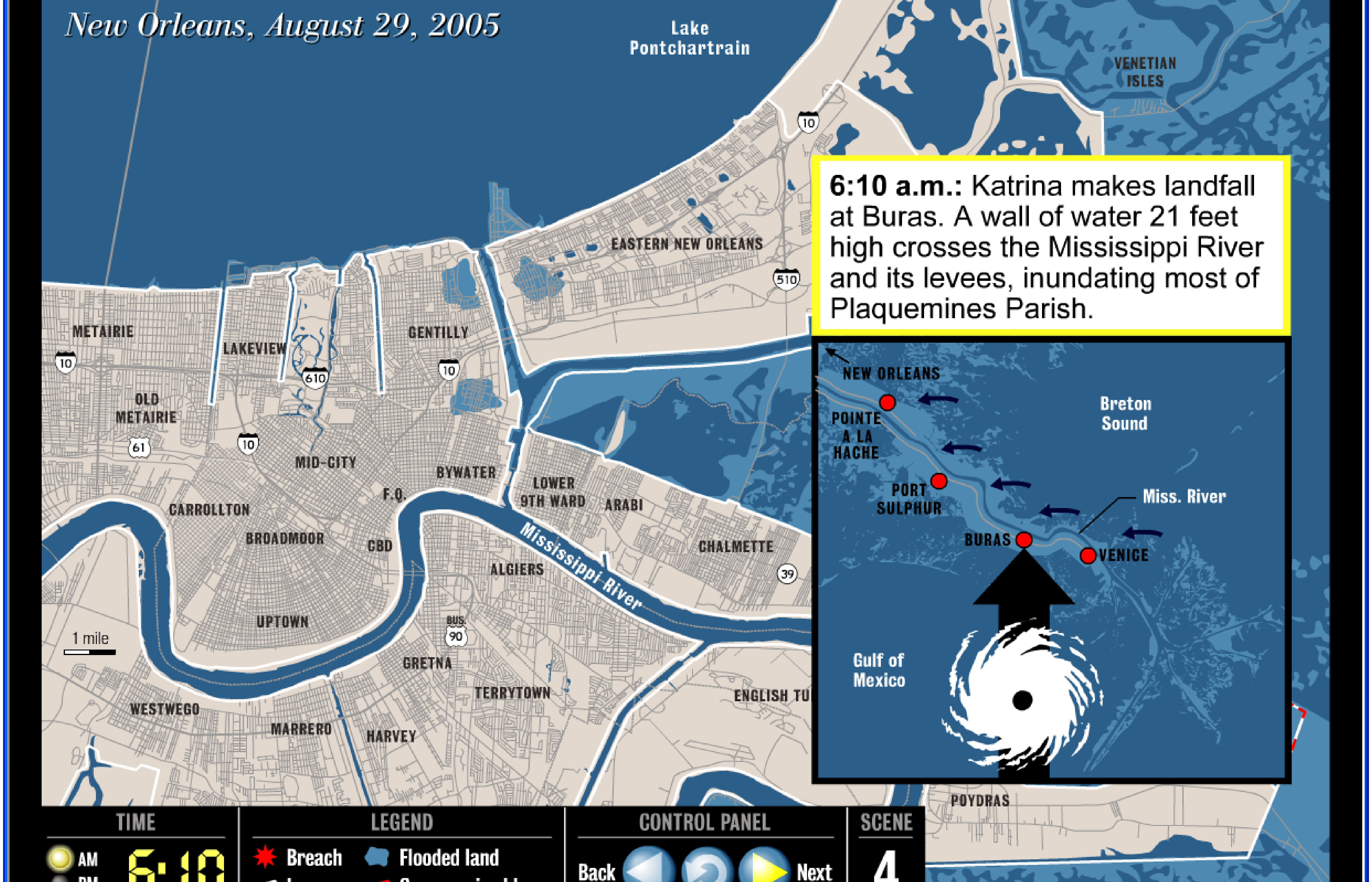
# FLASH FLOOD

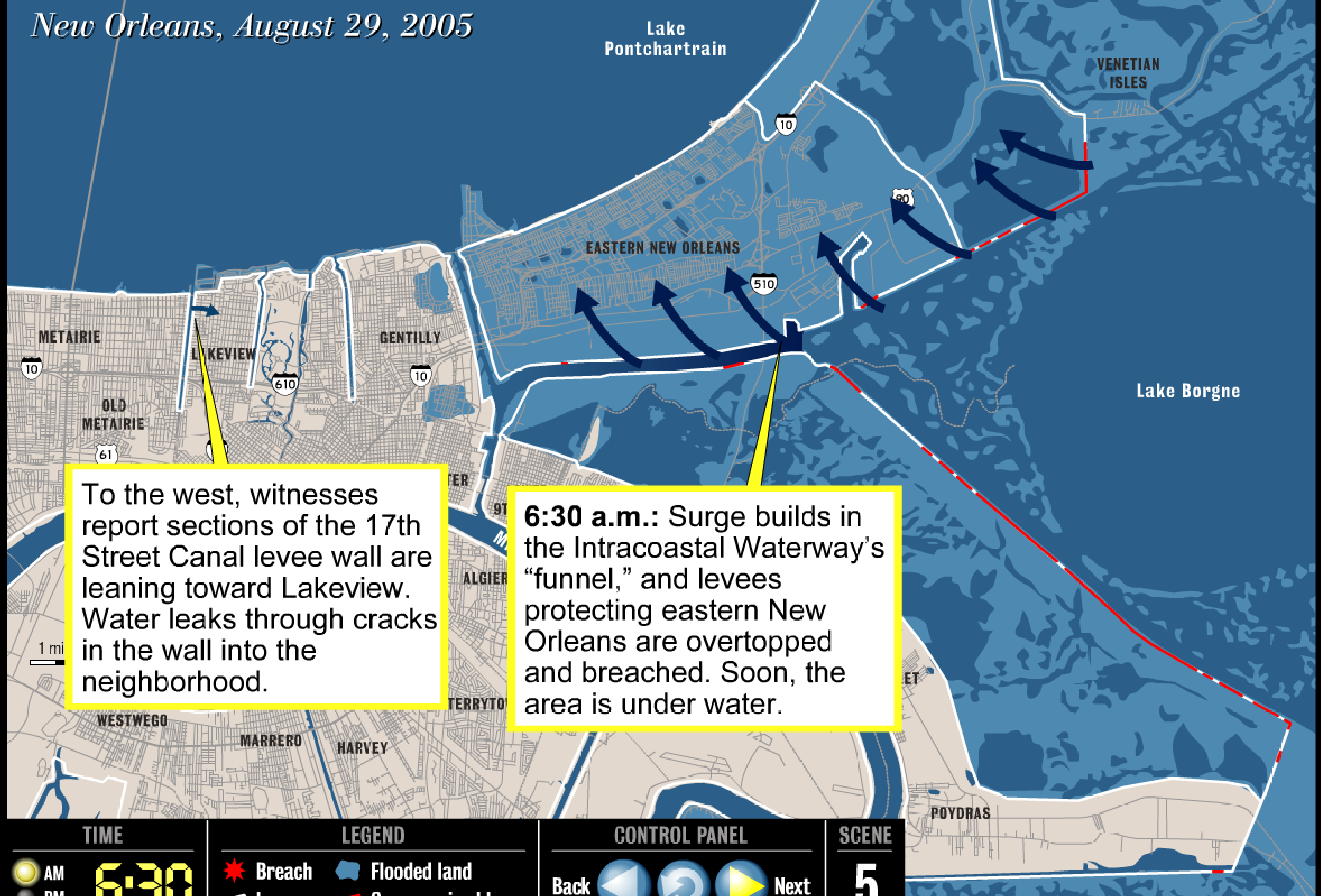
*Hurricane Katrina's Inundation of New Orleans, August 29, 2005*

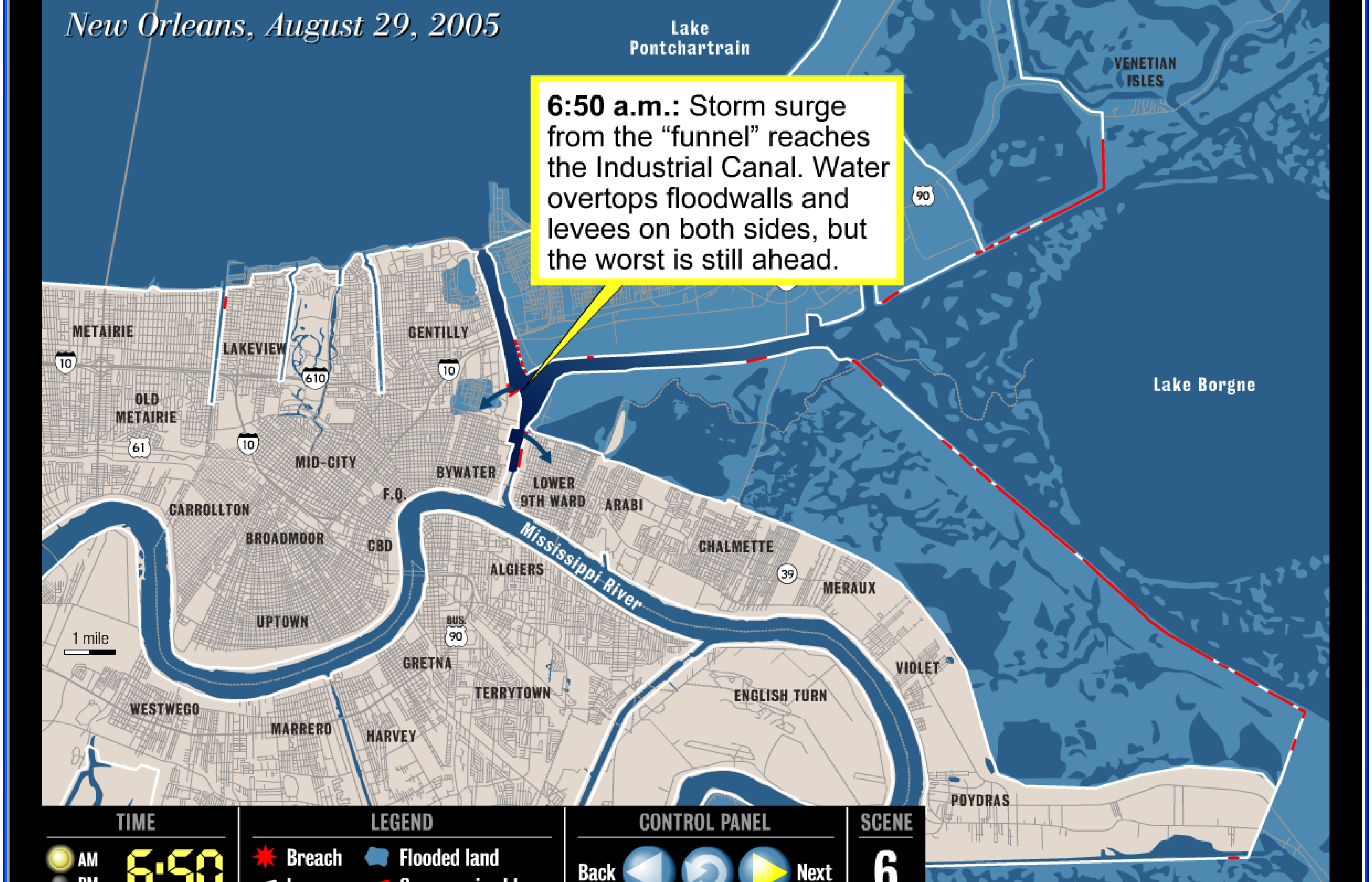
— By Dan Swenson, staff artist —


New Orleans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
F.Q.
CARROLLTON
BROADMOOR
CBD
ALGIERS
UPTOWN
GRETNA
TERRYTOWN
WESTWEGO
MARRERO
HARVEY
POYDRAS
Lake Borgne
1 mile
**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.
TIME
AM
4:30
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
2

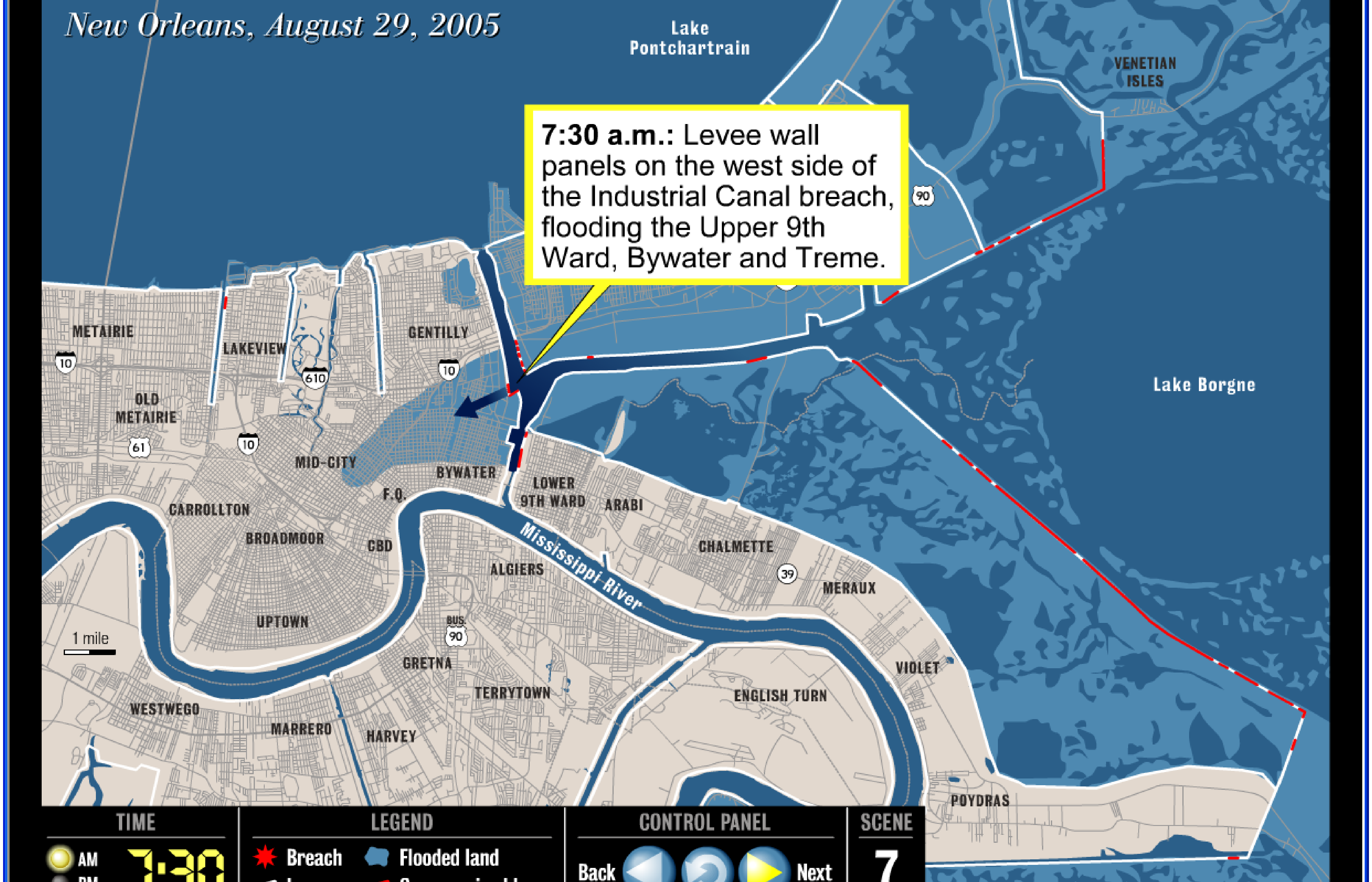

New Orleans, August 29, 2005
5 a.m.: Katrina's storm surge begins pounding the MR-GO levee. By dawn, levee sections crumble and Lake Borgne advances into wetlands toward St. Bernard Parish.
Lake Pontchartrain
EASTERN NEW ORLEANS
Lake Borgne
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
LOWER 9TH WARD
ARABI
F.Q.
CARROLLTON
BROADMOOR
CBD
Mississippi River
ALGIERS
CHALMETTE
MERAUX
UPTOWN
GRETNA
VIOLET
TERRYTOWN
ENGLISH TURN
WESTWEGO
MARRERO
HARVEY
POYDRAS
1 mile
10
610
510
61
39
BUS. 90
TIME
AM
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
3


New Orleans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
F.Q.
LOWER 9TH WARD
ARABI
CARROLLTON
BROADMOOR
CBD
CHALMETTE
ALGIERS
Mississippi River
UPTOWN
1 mile
GRETNA
TERRYTOWN
ENGLISH TU
WESTWEGO
MARRERO
HARVEY
POYDRAS
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.
NEW ORLEANS
POINTE A LA HACHE
Breton Sound
PORT SULPHUR
Miss. River
BURAS
VENICE
Gulf of Mexico
TIME
AM
6:10
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
4


New Orleans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
Lake Borgne
To the west, witnesses report sections of the 17th Street Canal levee wall are leaning toward Lakeview. Water leaks through cracks in the wall into the neighborhood.
**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.
ALGIER
WESTWEGO
MARRERO
HARVEY
POYDRAS
1 mi
TIME
AM
6:30
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
5

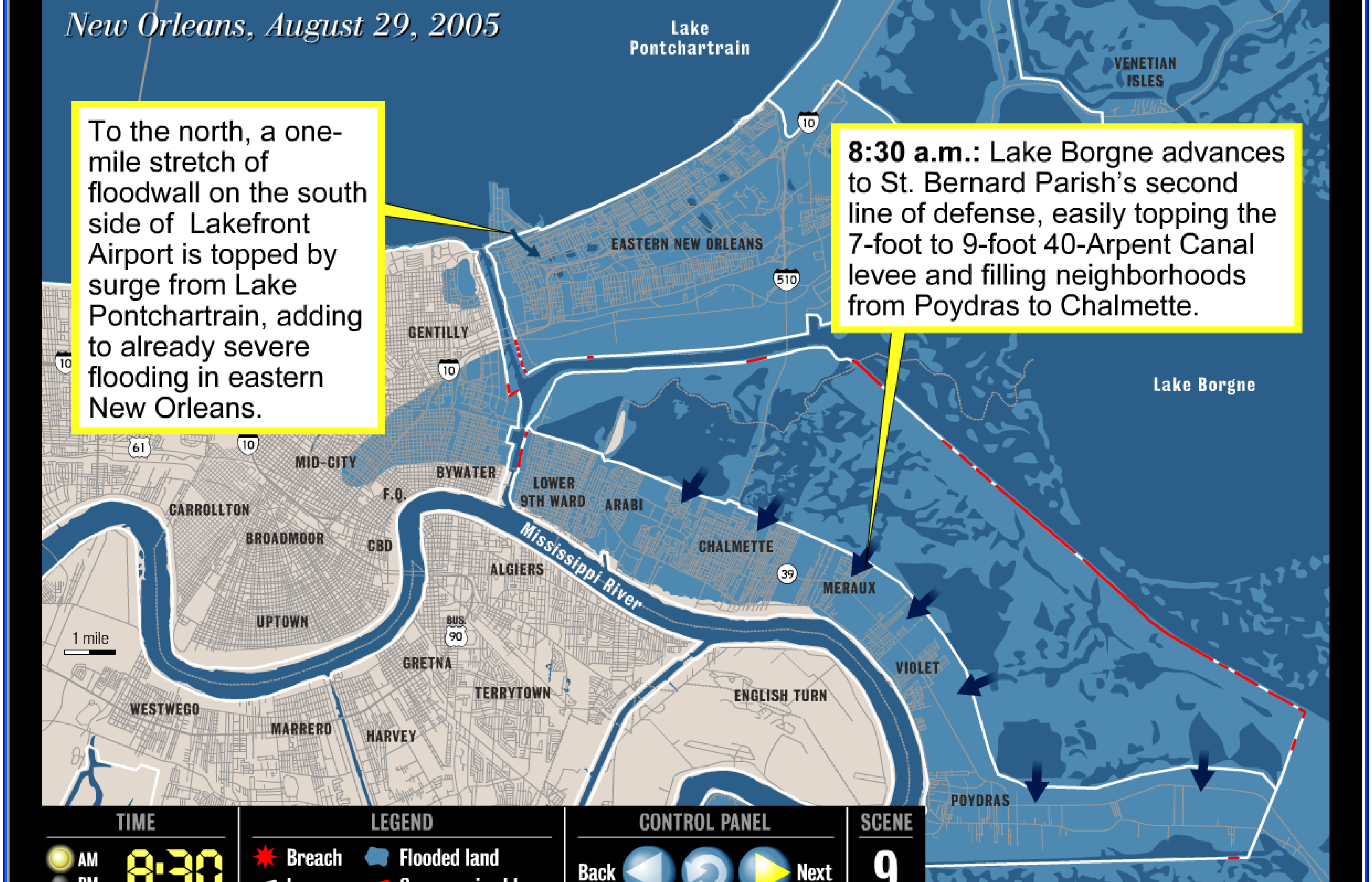


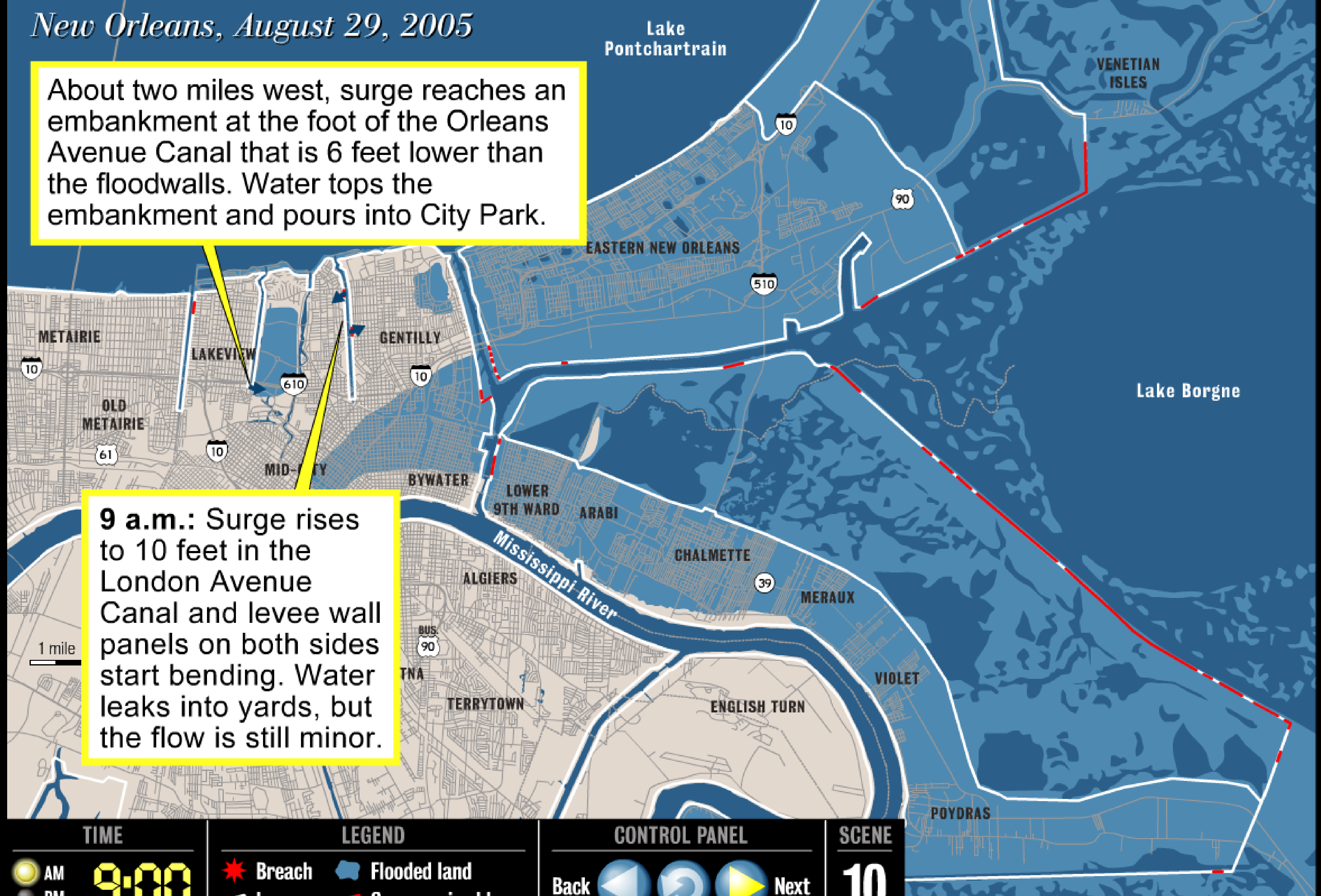
New Orleans, August 29, 2005
Lake Pontchartrain
6:50 a.m.: Storm surge from the "funnel" reaches the Industrial Canal. Water overtops floodwalls and levees on both sides, but the worst is still ahead.
VENETIAN ISLES
Lake Borgne
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
LOWER 9TH WARD
ARABI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

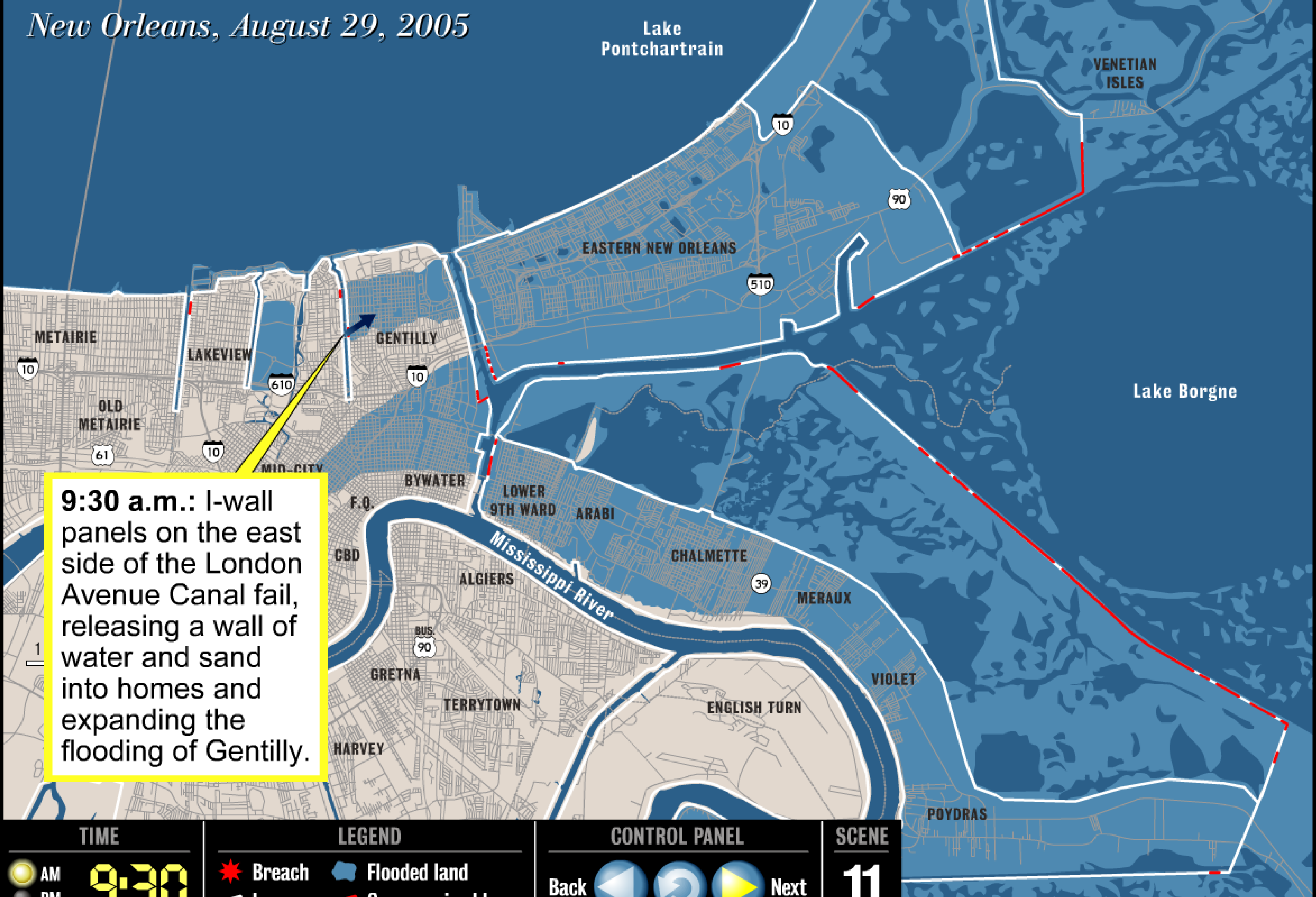


New Orleans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
7:30 a.m.: Levee wall panels on the west side of the Industrial Canal breach, flooding the Upper 9th Ward, Bywater and Treme.
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
LOWER 9TH WARD
ARABI
F.Q.
CARROLLTON
BROADMOOR
CBD
ALGIERS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

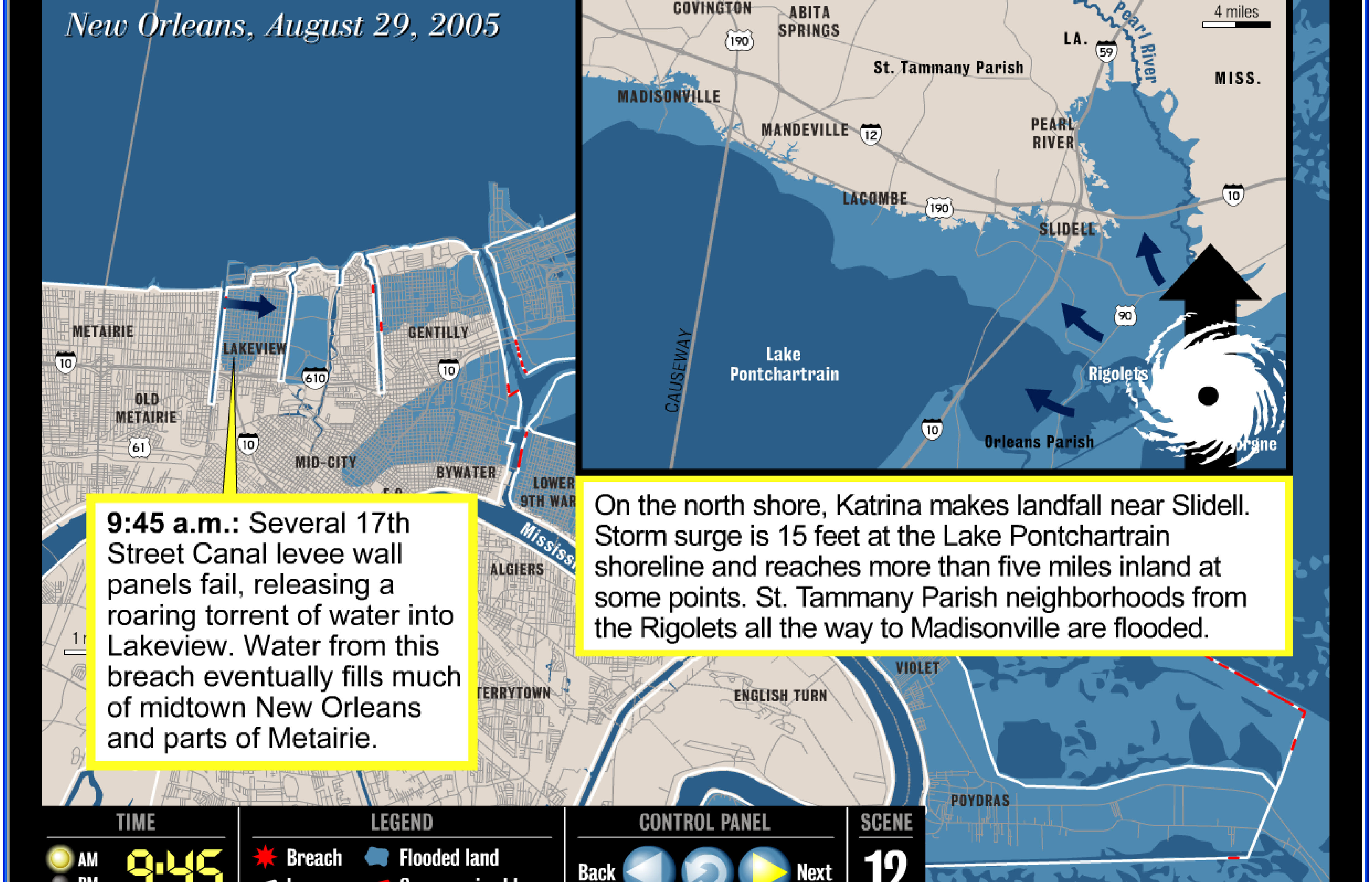
New Orleans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
LOWER 9TH WARD
ARABI
CARROLLTON
F.Q.
BROADMOOR
CBD
ALGIERS
Mississippi River
CHALMETTE
MERAUX
VIOLET
ENGLISH TURN
POYDRAS
Lake Borgne
10
610
61
90
510
39
**7:45 a.m.:** Two floodwall sections on the east side of the Industrial Canal fall, releasing a wall of water into the Lower 9th Ward, tossing homes and cars around like toys. The water also pours into Arabi and Chalmette.
TIME
AM
7:45
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
8


New Orleans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
To the north, a one-mile stretch of floodwall on the south side of Lakefront Airport is topped by surge from Lake Pontchartrain, adding to already severe flooding in eastern New Orleans.
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.
10
510
EASTERN NEW ORLEANS
GENTILLY
Lake Borgne
61
MID-CITY
BYWATER
LOWER 9TH WARD
ARABI
F.Q.
CARROLLTON
BROADMOOR
CBD
CHALMETTE
39
MERAUX
ALGIERS
Mississippi River
UPTOWN
BUS 90
1 mile
GRETNA
VIOLET
TERRYTOWN
ENGLISH TURN
WESTWEGO
MARRERO
HARVEY
POYDRAS
TIME
AM
8:30
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
9


New Orleans, August 29, 2005
About two miles west, surge reaches an embankment at the foot of the Orleans Avenue Canal that is 6 feet lower than the floodwalls. Water tops the embankment and pours into City Park.
9 a.m.: Surge rises to 10 feet in the London Avenue Canal and levee wall panels on both sides start bending. Water leaks into yards, but the flow is still minor.
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
LOWER 9TH WARD
ARABI
CHALMETTE
MERAUX
ALGIERS
Mississippi River
Lake Borgne
TERRYTOWN
ENGLISH TURN
VIOLET
POYDRAS
1 mile
10
90
510
610
61
39
BUS. 90
TIME
AM
9:00
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
10



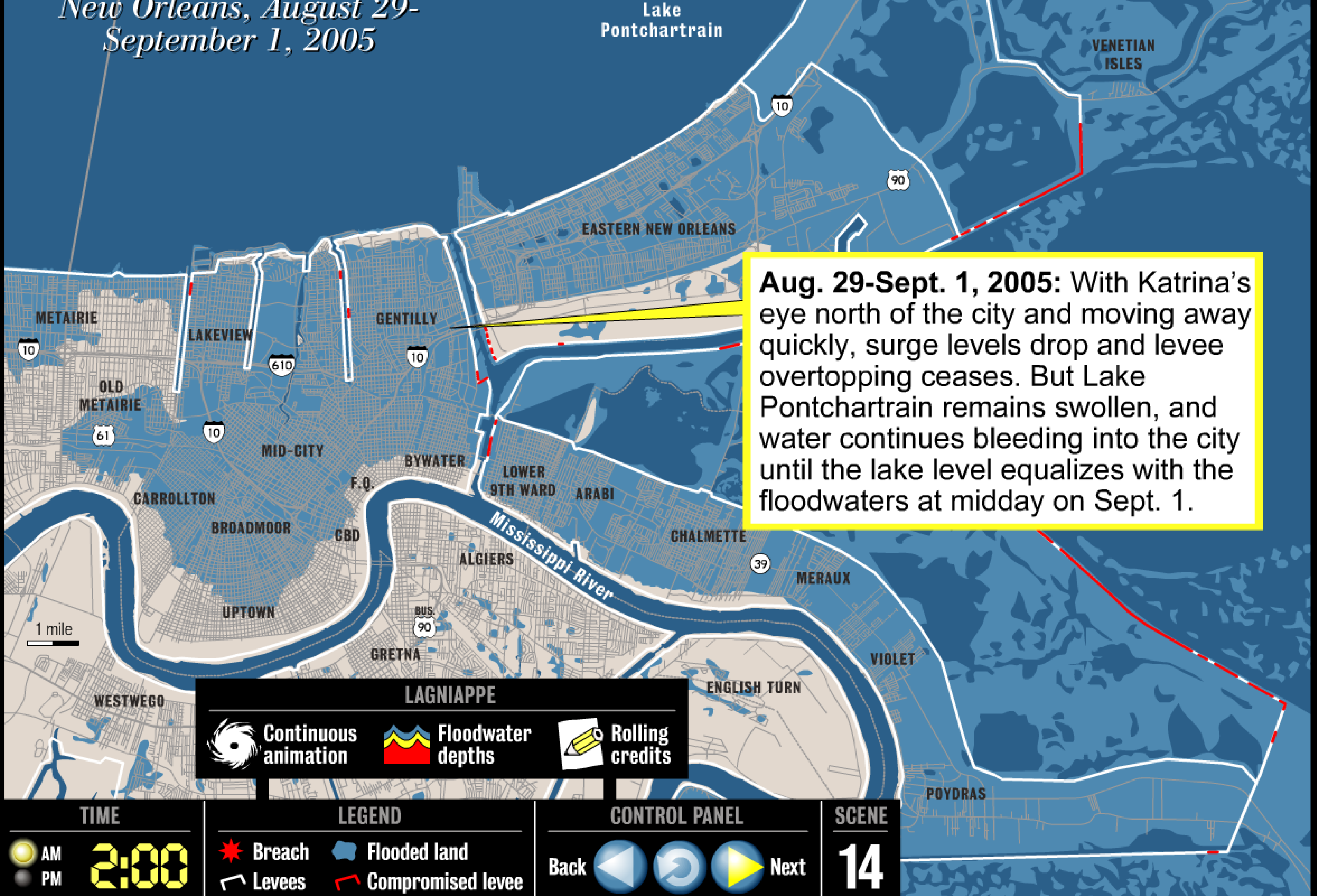
New Orleans, August 29, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
Lake Borgne
BYWATER
LOWER 9TH WARD
ARABI
F.Q.
CBD
ALGIERS
Mississippi River
CHALMETTE
MERAUX
GRETNA
TERRYTOWN
ENGLISH TURN
VIOLET
HARVEY
POYDRAS
9:30 a.m.: I-wall panels on the east side of the London Avenue Canal fail, releasing a wall of water and sand into homes and expanding the flooding of Gentilly.
TIME
AM
9:30
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
11




**9:45 a.m.:** Several 17th Street Canal levee wall panels fail, releasing a roaring torrent of water into Lakeview. Water from this breach eventually fills much of midtown New Orleans and parts 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.


New Orleans, 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.
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
F.Q.
LOWER 9TH WARD
ARABI
CBD
ALGIERS
CHALMETTE
MERAUX
Mississippi River
Lake Borgne
GRETNA
TERRYTOWN
ENGLISH TURN
VIOLET
HARVEY
POYDRAS
Parts of Jefferson Parish also flood as rainwater leaks through an unstaffed pumping system.
TIME
AM
10:30
LEGEND
Breach
Flooded land
CONTROL PANEL
Back
Next
SCENE
13


New Orleans, August 29-
September 1, 2005
Lake Pontchartrain
VENETIAN ISLES
EASTERN NEW ORLEANS
METAIRIE
LAKEVIEW
GENTILLY
OLD METAIRIE
MID-CITY
BYWATER
LOWER 9TH WARD
ARABI
F.Q.
CARROLLTON
BROADMOOR
CBD
ALGIERS
CHALMETTE
MERAUX
Mississippi River
UPTOWN
GRETNA
VIOLET
ENGLISH TURN
WESTWEGO
POYDRAS
1 mile
10
610
61
90
BUS. 90
39
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.
LAGNIAPPE
Continuous animation
Floodwater depths
Rolling credits
TIME
AM
PM
2:00
LEGEND
Breach
Flooded land
Levees
Compromised levee
CONTROL PANEL
Back
Next
SCENE
14

# The Hurricane and Storm Damage Risk Reduction System (HSDRRS)

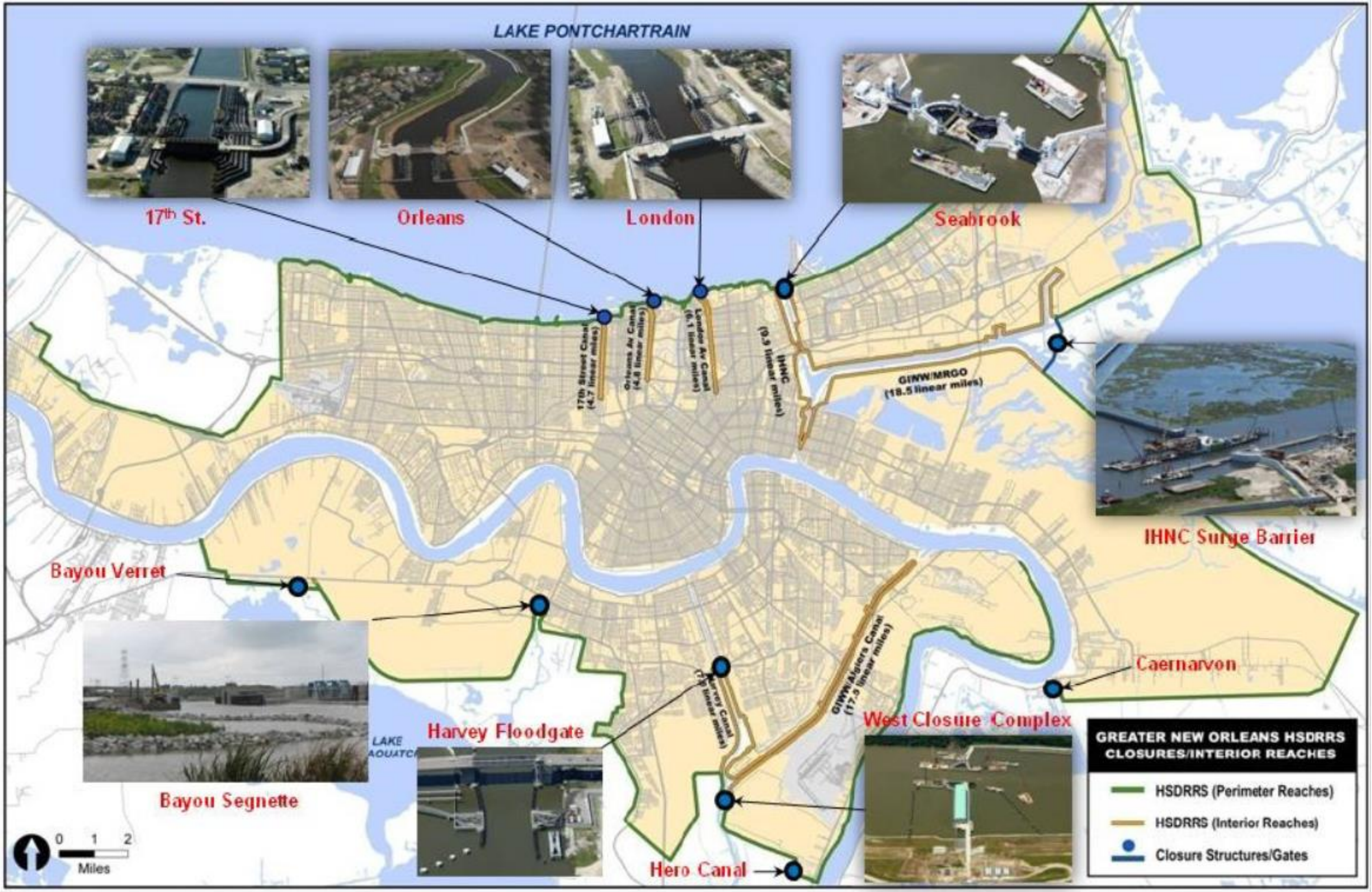
http://www.mvn.usace.army.mil/Missions/HSDRRS.aspx

Four strategic improvements:

1) Block five storm surge avenues from 100-year surge
2) Raise and strengthen levees and floodwalls
3) Make sure designs are consistent
4) Improve and stormproof key pump stations

# Some HSDRRS facts

- 350 miles of levees and floodwalls, including interior levees and floodwalls, hundreds of gates and structures for sealing the system
- Armoring against erosion, back-scouring, and at transition points between levees and structures with turf mat topped with sod; research ongoing for other types of armoring
- Clay used for levees is 93 million cubic years (fills 21 Superdomes)
- 78 pumping stations (federal and non-federal)
- Gulf Intracoastal Waterway – West Closure Complex;
- Inner Harbor Navigation Canal Surge Barrier; world's largest surge barrier
- Seabrook Floodgate Complex;
- Interim closure structures and pump stations for the three outfall canals


LAKE PONTCHARTRAIN
17th St.
Orleans
London
Seabrook
17th Street Canal (4.7 linear miles)
Orleans Av Canal (4.8 linear miles)
London Av Canal (6.1 linear miles)
IHNC (9.9 linear miles)
GIWW/MRGO (18.5 linear miles)
IHNC Surge Barrier
Bayou Verret
Bayou Segnette
Harvey Floodgate
Harvey Canal
GIWW/Algiers Canal (17.5 linear miles)
West Closure Complex
Caernarvon
Hero Canal
GREATER NEW ORLEANS HSDRRS CLOSURES/INTERIOR REACHES
HSDRRS (Perimeter Reaches)
HSDRRS (Interior Reaches)
Closure Structures/Gates
0 1 2
Miles

# Storm Proof Key Pump Stations

***Repair 61 pump stations ($103 Mil)***

***Storm proof 49 pump stations ($322 Mil)***

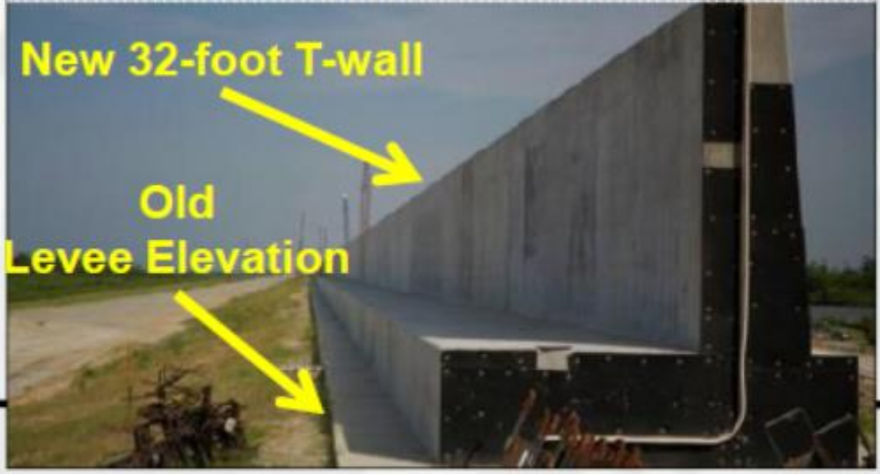
***Construct 5 safe houses ($18 Mil)***

# Raise and Strengthen Levees / Floodwalls

Higher Floodwalls and Levees

Orleans Metro

St. Bernard Parish





New Orleans East


Up to 31.5 ft in ST. Bernard Parish, for example)

# Surge barrier ("The Wall")

- 1.8 miles
- 25-26 feet above sea level
- 2 floodgates

# Seabrook floodgate

# Levee expansion, west side of Mississippi River

# Joint probability methods for hazard assessment

Synthetic hurricane track dataset → 2D wind and pressure fields → Surge model. Coupling with other relevant water level processes (wave, tide, etc) → Determination of elevation–frequency curves at dense points throughout the region using Joint Probability Methods (JPM) → Application

Variations for intensity, speed and size

Brute force JPM can require simulations on order of 10,000s

*Application examples*

- Flood Insurance Rate Maps (FIRMs)
- Levee height design
- Elevation or protection design for nuclear plants

# How "100-year" surge event is determined (full JPM)

- Develop probability distributions for each storm parameter ($R_{max}$, intensity, etc.) from observations
- Establish rate of storm occurrence in space and time
- Subdivide each distribution into a small number of discrete pieces (i.e., 6 values)
- Construct all possible hypothetical  tracks by taking all possible combinations of the storm quantities. For example, with six values for four parameters one constructs 1296 "storms." (=6 pressure X 6 $R_{max}$ X 6 direction X 6 speed)
- Conduct hydrodynamic simulations (surge model, wave coupling, sometimes hydrology) with multiple tracks for each storm type sufficiently spaced for shoreline influence (landfall and bypassing). Track spacing is typically one $R_{max}$, or about ten tracks per site (12,960 simulations)
- For each storm, compute highest surge for locations of interest, tag it with rate of occurrence
- Construct a histogram of rate versus surge height
- Find the 1% surge elevation for each location

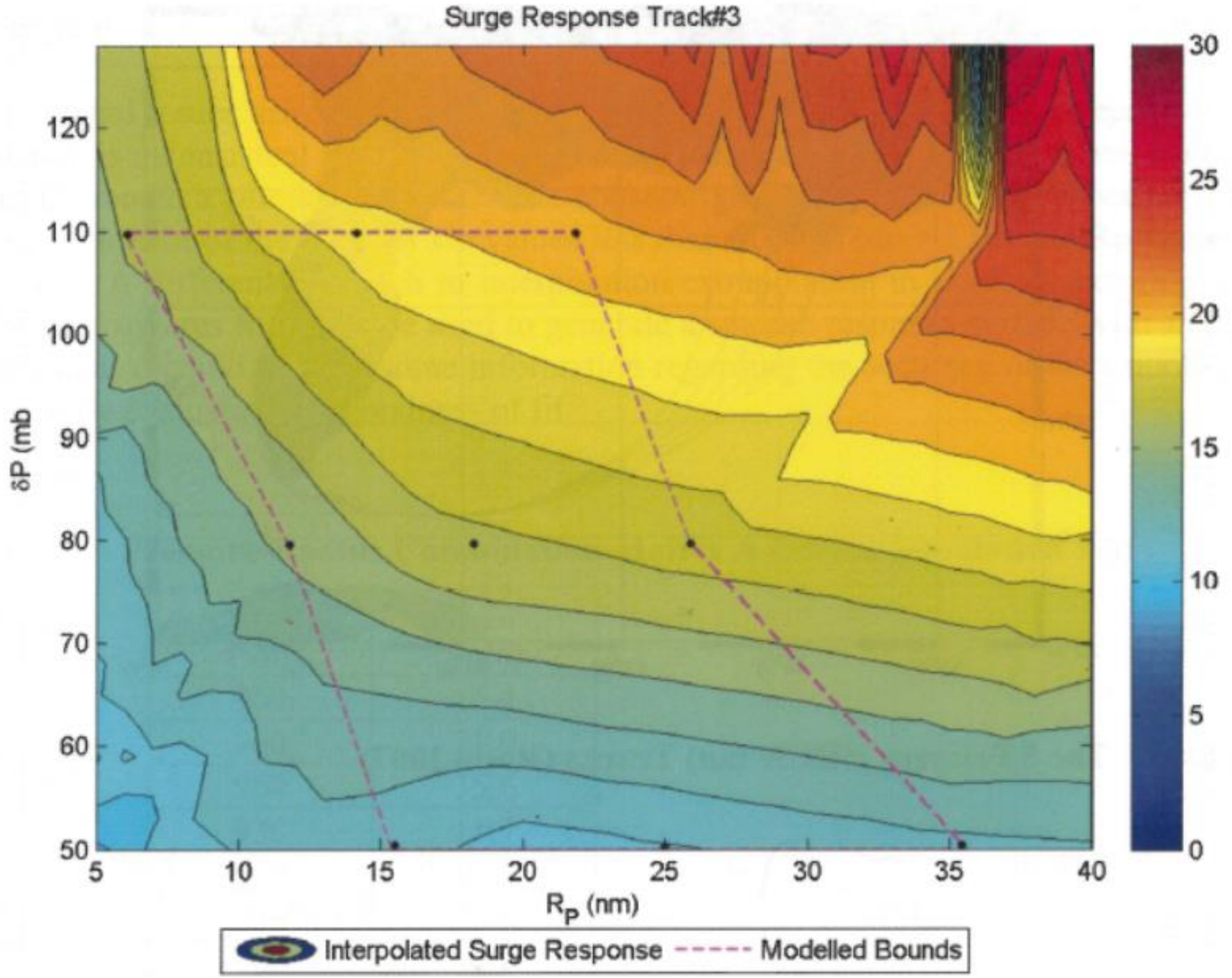
# “Optimized sampling” (OS)

- Brute force JPM not feasible using high-resolution hydrodynamic models (i.e., ADCIRC coupled with a wave model)
- JPM-OS techniques seeks to reduce the number of simulations in an intelligent way (fewer combinations, tracks) while maintaining accurate frequency return values

# Response Surface Method

- Restricts parameters based on sensitivity response experiments (i.e. only three pressure values chosen). It is found certain combinations are linear, some responses stronger than others, and "smooth"
- Carefully choosing parameters limits combinations, and reduces simulations
- Steps used for JPM-OS-R for HSDRRS design:
  - Step 1: Start with ~5 tracks roughly perpendicular to landfall region and a few values of p and $R_{max}$. Conduct the simulations. Interpolate or extrapolate other surge values in the p-$R_{max}$ plane
  - Step 2: Add a few more oblique angles ( ±45°), simulate on a reduced p-$R_{max}$ combination (compared to Step 1), interpolate/extrapolate
  - Step 3: Vary by a few storm speed parameters, simulate on a further reduced p-$R_{max}$ combination (compared to Step 2), interpolate/extrapolate
  - Step 4: Interpolate/extrapolate in track space for one p and $R_{max}$
- This process yielded over 50,000 storms.
- Problems with JPM-OS-R are in choosing the proper parameters restrictions (needs expert judgment) which can also be arbitrary; the accuracy of the interpolation; and the use of extrapolation.

# Example of interpolation/extrapolation in Step 1 for one track




Interpolated/extrapolated surge response function in $\Delta p$-$R_{max}$ plane for one track. $\Delta p$ is central pressure minus environmental pressure.

Black dots indicate 9 simulated storms for this track. The magenta dashed polygon indicated where bilinear interpolation is performed.

Below 110 mb, and to the right and left of the polygon, the response surface is extrapolated by maintaining a constant $\Delta p$-$R_{max}$ gradient from the edge of the polygon.

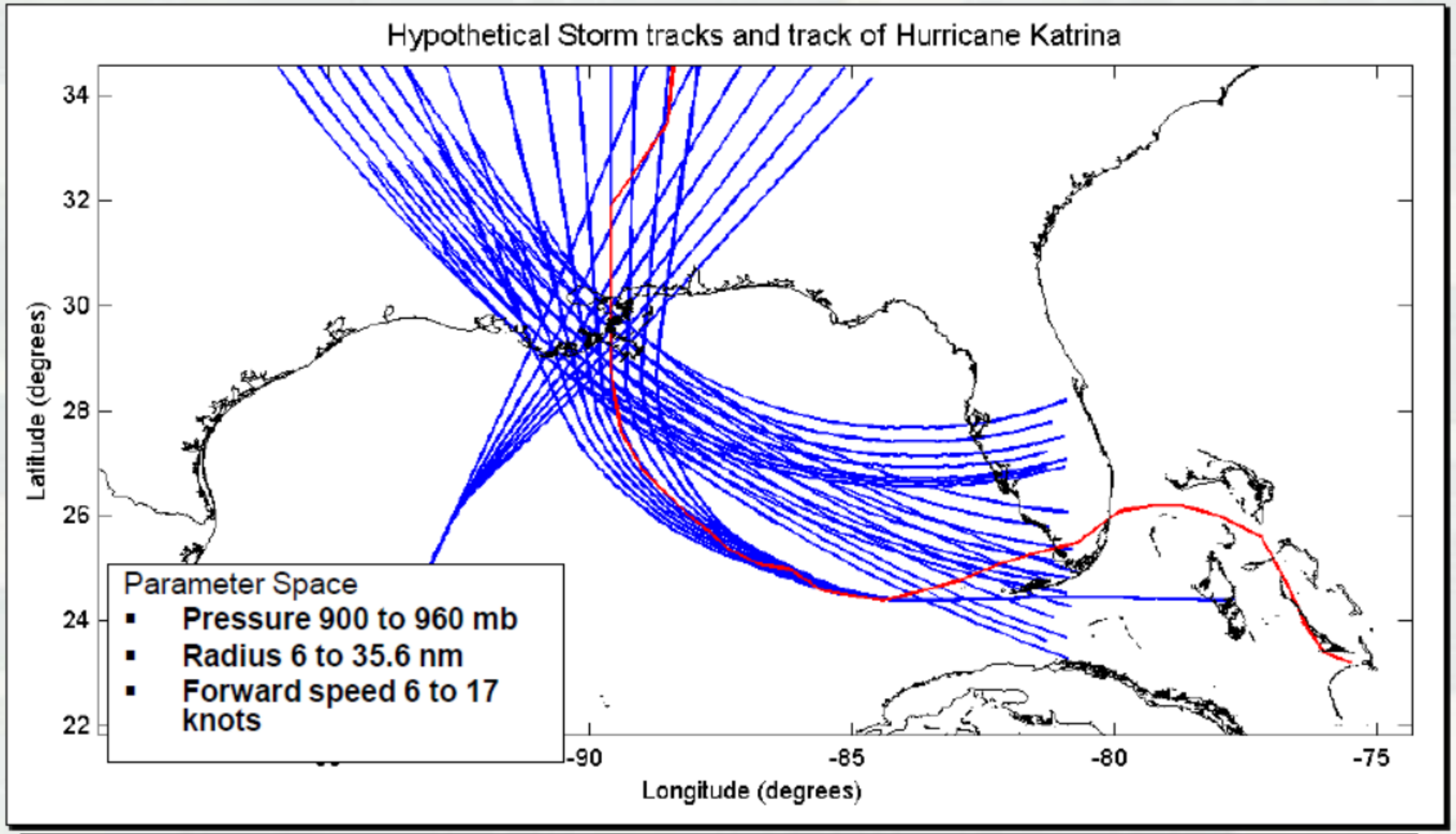
Above 110 mb, the surge response function is extrapolated by maintaining a constant p gradient.

# JPM-OS-R applied to the post-Katrina New Orleans levees reconstruction

Table 1. Summary of the 152 HSDRRS JPM-OS hurricane tracks, stratified by central pressure, radius of maximum winds, translation speed, track direction, primary and secondary plus intensity (Saffir-Simpson scale), and number of storms in each group. From Jacobsen (2013).

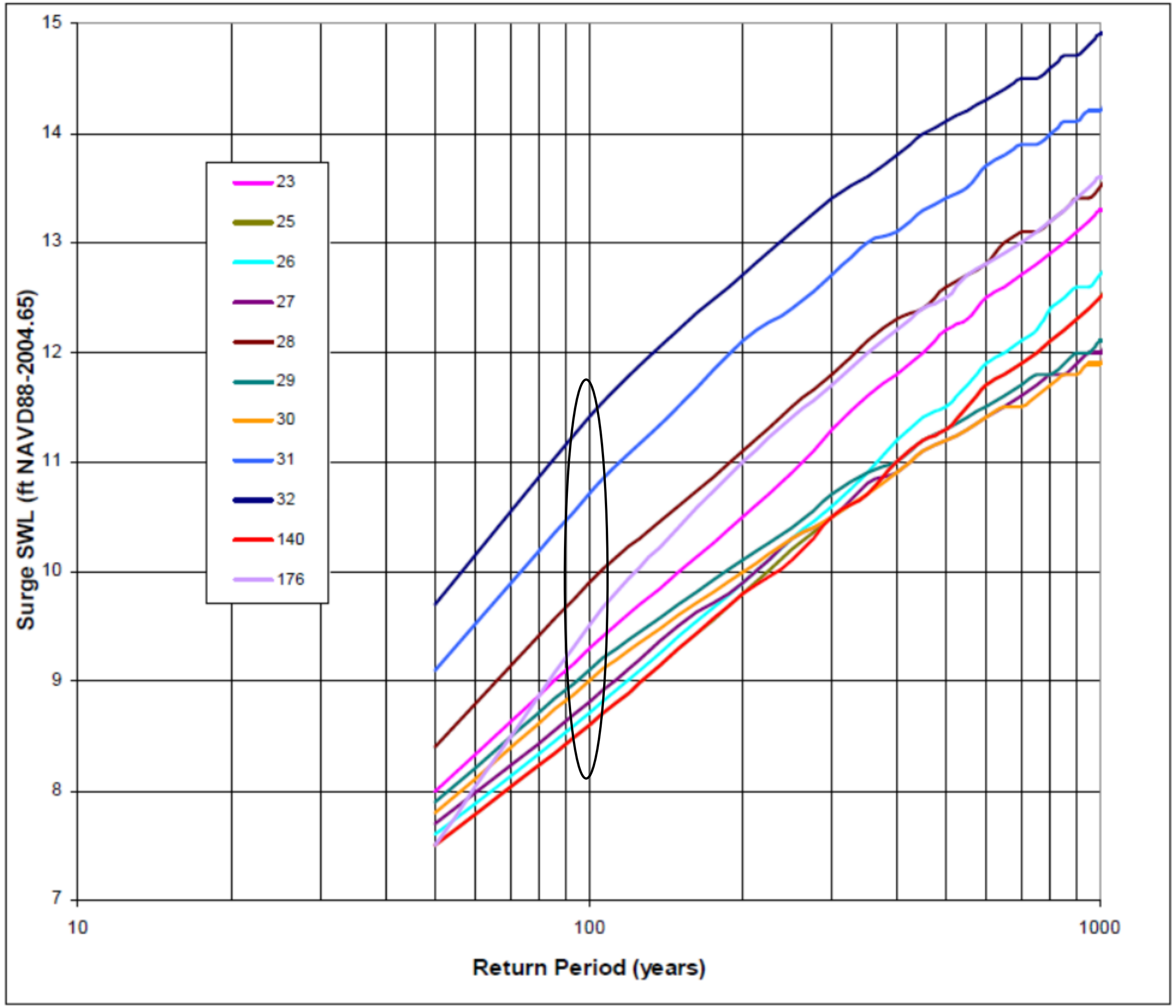
| GoM CP mb | GoM $R_{max}$ miles | Landfall $V_f$ mph | θ direction from | Track Set (Number) |
|---|---|---|---|---|
| 960 | 40.9 | 12.7 | Central | P (5) |
| | 28.3 | 12.7 | SE | P (4) |
| | | | SW | P (4) |
| | 24.2 | 12.7 | Central | P (5) |
| | 20.9 | 12.7 | SE | P (4) |
| | | | SW | P (4) |
| | 20.4 | 12.7 | Central | S (4) |
| | | | SE | S (3) |
| | | | SW | S (3) |
| | | 6.9 | Central | P (5) |
| | | | | S (4) |
| | 12.7 | 12.7 | Central | P (5) |
| 930 | 29.7 | 12.7 | Central | P (5) |
| | 20.4 | 19.6 | Central | P (5) |
| | | | | S (4) |
| | | | SE | P (4) |
| | | | | S (3) |
| | | | SW | P (4) |
| | | | | S (3) |
| | | 12.7 | Central | P (5) |
| | | 6.9 | SE | P (4) |
| | | | | S (3) |
| | | | SW | P (4) |
| | | | | S (3) |
| | 9.2 | 12.7 | Central | P (5) |
| 900 | 25.1 | 12.7 | Central | P (5) |
| | 21.2 | 12.7 | SE | P (4) |
| | | | SW | P (4) |
| | 20.4 | 12.7 | Central | S (4) |
| | | | SE | S (3) |
| | | | SW | S (3) |
| | | 6.9 | Central | P (5) |
| | | | | S (4) |
| | 17.1 | 12.7 | Central | P (5) |
| | 14.4 | 12.7 | SE | P (4) |
| | | | SW | P (4) |
| | 6.9 | 12.7 | Central | P (5) |
| **3 CP** | **15 CP-$R_{max}$** | **19 CP-$R_{max}$-$V_f$** | **30 CPD-$R_{max}$-$V_f$-θ** | **152 Storms** |

# Selection of Synthetic Storms



# Example 100-year surge curves for southshore

# Example 100-year surge curves for southshore



| Test Parameter | Approximate Sensitivity Magnitude (feet) | Notes |
|---|---|---|
| Weirs | 2 | Dependant on location of weir boundaries |
| Wetting and Drying (H0) | 0.5 | In areas that draw down first |
| BFCdLLimit | 3 | Depends on Manning's n specification, interacts with wind drag |
| NOLICA, NOLICAT | 0 | N/A |
| Sector based wind drag formulation | 3 | Interacts with BFCdLLimit and Manning's n |
| Manning's n smoothness | 0 | N/A |
| Land cover data | 2 | Need accurate data |
| Meteorological baseline | 2 | Need to compare multiple wind models |
| Storm Track | 2 | Closer spacing needed to capture peak in surge response |
| Forward Speed | 3 | Becomes increasingly non-linear for locations farther from open Gulf, more uncertainty for slower storms |
| Holland B | 2 | Broad impact |

# HSDRRS concerns

CPRA, 2013: GNO flood protection system notice of construction completion design assessment by Non-Federal Sponsor. DNR Contract File No. 2503-11-61

The Water Institute of the Gulf, 2014: Expert review panel on Greater New Orleans Hurricane and Storm Damage Risk Reduction System Design Guidelines.

# Concerns about the HSDRSS system

- JPM concerns
  a) Lack of Category 5 hurricane in training set
  b) Lack of storms tracking from east in training set
  c) Interpolation/extrapolation used in JPM-OS response function do not guarantee accurate results
  d) Code had typos (fortunately, very minor impact on results)
  e) Storm size not explicitly modelled
  f) Do the sensitivity results add error or have a “cancelling out” effect?
  g) Future assessments should also include other JPM-OS schemes
- Fortunately, the JPM-OS included a Gaussian residual error term to acknowledge uncertainty and to add some conservativeness. However, it also reduces surge values for lower return periods, which is inconsistent with the philosophy of adding uncertainty.
- Other concerns
  a) Do “100-year” return levels sufficiently reduce the risk of another flooding event?
  b) Breaking wave formulations need further evaluation
  c) Overtopping rate formulation need further evaluation
  d) Is sea-level rise underestimated? It may be 3-4 feet, and it’s not site specific. “Levee lifts” are planned every ten years
  e) Corps is monitoring of settlement, corrosion, structural integrity, and slope stability. But is more oversight needed?

Figure 4. Differential settlement at transition between T-Wall for Lake Borgne Closure (background) and earthen Levee for New Orleans east back segment (foreground) - Taken by R. Gilbert on July 16, 2013.


Figure 5. Shallow slope failure near toe of earthen levee for New Orleans east back segment. Numbered arrows indicate sampling locations for a previous study. (Provided by R. Brouillette, CPRA).

# Future assessment of the HSDRSS system

- The New Orleans risk reduction system is a remarkable engineering achievement, completed relatively quickly in difficult circumstances.
- Also spurred new developments in storm surge modelling and JPM methodologies
- Army Corps of Engineers and all evaluators, however, have noted issues, and have recommended a reanalysis every ten years based on lessons learned, evolving infrastructure issues, and latest science. original analysis 2007/2008, so next one should be completed 2017/2018.