IN THE UNITED STATES COURT OF FEDERAL CLAIMS

ST. BERNARD PARISH GOVERNMENT AND OTHER OWNERS OF REAL PROPERTY IN ST. BERNARD PARISH OR THE LOWER NINTH WARD OF THE CITY OF NEW ORLEANS,	
Plaintiffs,	No. 05-1119 L
v.	
	Honorable Susan G. Braden
UNITED STATES OF AMERICA,	
Defendant.	

DIRECT TESTIMONY OF JOANNES J. WESTERINK, PhD

In accordance with the Court's pre-trial schedule Order of October 21, 2013 (ECF No. 227), the United States submits the following direct testimony by affidavit of Joannes J. Westerink, PhD. Based upon the qualifications and experience of Dr. Westerink, as detailed in his direct testimony and summarized in the *curriculum vitae* identified as Defendant's Valuation Exhibit No. 2 ("DVX-2"), the United States requests that Dr. Westerink be qualified as an expert in civil engineering, with a specialty in hydraulics, coastal engineering, computational hydraulics, and computer modeling. The United States further moves for the admission of Dr. Westerink's Expert Report (DVX-1)

Direct Testimony of Joannes Jacobus Aloysius Westerink, Ph.D.

Joseph and Nona Ahearn Endowed Professor
Henry J. Massman Department Chairman
Department of Civil & Environmental Engineering & Earth Sciences
University of Notre Dame
Notre Dame, IN

St. Bernard Parish v. United States
Case 05-1119 (Fed. Cl.)
November 12, 2013

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Purpose of the Study

- To inform the valuation phase of this case, I was asked by the United States Department of Justice to study the flooding experienced at eleven specific plaintiff-owned properties (Plaintiff Properties listed in Table 1) in the Lower Ninth Ward of New Orleans and St. Bernard Parish during Hurricane Katrina.
- The Study Area extends along the Inner Harbor Navigation Canal (IHNC), the Mississippi River Gulf Outlet (MRGO) Reach 1, and the MRGO Reach 2, and encompasses St. Bernard Polder and vicinity, Figure 1.
- This study describes the surge or specifically *surface water elevations* that are the combined effect of the winds, atmospheric pressure, waves, riverine flow, and tides that occurred during Hurricane Katrina. The surface water levels reported in this Study are in feet (ft) and are referenced to the vertical datum NAVD88 (2004.65). The actual depth of the water at any position must add ground elevations lying *below* zero NAVD88 (2004.65) and must subtract ground elevations lying *above* zero NAVD88 (2004.65).

Purpose of the Study

- Eleven Plaintiff-owned properties are the subject of this Study. For reference, these properties have been assigned numbers and abbreviated names reflecting their relative location throughout the Study Area.

Property Identifier Number	Property Identification Used in this Report	Detailed Property Description
1	"Adams"	2414 Deslonde St., New Orleans, LA
2	"StBP #1"	1818 Center Street, Arabi, LA
3	"StBP #2"	8600 Victory Dr., Chalmette, LA
4	"Tommaseo"	3641-3616 Fenelon St., Chalmette, LA
5	"StBP #3"	E. Josephine & Marietta, Chalmette, LA
6	"StBP #4"	E. Judge Perez & Judy Dr., Meraux, LA
7	"Steve's RV"	E. 3209 Judge Perez, Meraux, LA
8	"StBP #5"	4119 E. Judge Perez, Meraux, LA
9	"Bordelon"	3024 Lakewood Dr., Violet, LA
10	"PSSI"	6325 Paris Rd. (Portions of Lot 5 (I and J)), St. Bernard Parish, LA
11	"Florissant"	2316 Florissant Hwy., St. Bernard Parish, LA

Table 1

Purpose of the Study

- The Study Area with breaches indicated in red lines along the IHNC and MRGO Reach 2 levees. Plaintiff's properties are indicated by the bright yellow triangles and numbered locations 1 - 11 and are described in Table 1.

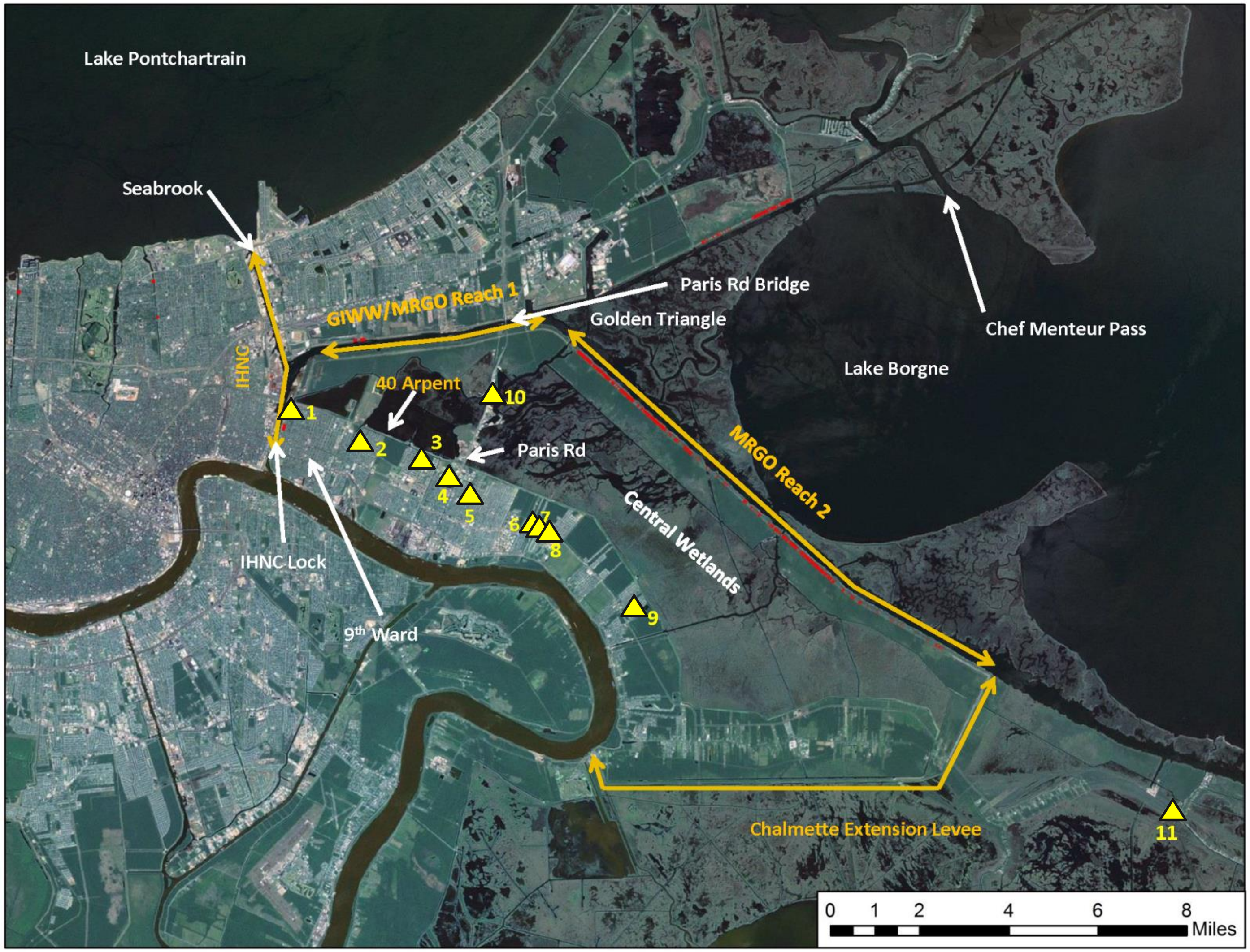

Figure 1

Purpose of the Study

- Hurricane Katrina flooded St. Bernard Polder through various pathways. In order to inform the valuation analyses for each Trial Property, I examined the flooding experienced in seven scenarios that quantify the following influences:
  - The breaches in the IHNC floodwalls during Hurricane Katrina;
  - Changes in the MRGO's shape from its completed authorized dimensions in 1968 to its actual dimensions in 2005;
  - Changes in wetland topography and roughness occurring between the commencement of construction of the MRGO project in 1958 to the time of Hurricane Katrina in 2005;
  - The existence of the MRGO channel itself;
  - The existence of the federal levees constructed around St. Bernard Polder along the MRGO's banks.
- The conditions for each of these seven scenarios are defined in Table 2.

Purpose of the Study

- Description of the seven scenarios simulated in this Study.

Scenario	MRGO Status	Marsh Status	Levee Breaches	Description
A1 (Katrina Actual Event Conditions)	2005 pre-Katrina dimensions	2005 pre-Katrina conditions	Breaching occurring as during Katrina	Base case: Actual Katrina Hindcast
A2 (2005 MRGO/ 2005 Wetlands/ IHNC Breaches Only)	2005 pre-Katrina dimensions	2005 pre-Katrina conditions	IHNC Breaches Only	Base case reflecting levee breaches only in the IHNC floodwall
B1 (MRGO As-Designed/1956 Wetlands)	MRGO at its authorized dimensions as of completion in 1968	1956 Wetland conditions	Breaching occurring as during Katrina	Katrina impact absent bank erosion channel widening/ wetland degradation
B2 (MRGO As-Designed/1956 Wetlands/IHNC Breaches Only)	MRGO at its authorized dimensions as of completion in 1968	1956 Wetland conditions	IHNC Breaches Only	Katrina impact absent bank erosion channel widening/ wetland degradation reflecting INHC breaches only
C (No MRGO/ 1956 Wetlands)	No MRGO	1956 Wetland conditions	Breaching occurring as during Katrina	Katrina impact without MRGO, and with 1956 wetland topography
D (No Federal Levees/2005 MRGO/2005 Wetlands)	2005 pre-Katrina dimensions	2005 pre-Katrina conditions	No levees along MRGO Reach 1 and 2	Katrina impact with MRGO but without levees along MRGO. MRGO and wetlands with 2005 conditions
E (No Federal Levees/No MRGO/1956 Wetlands)	No MRGO	1956 Wetland conditions	No levees along MRGO Reach 1 and 2	Katrina impact with no federal influence

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Principal Findings: *Katrina Actual Event Conditions Hindcast (Scenario A1)*

- My hindcast of the historical storm surge and wave conditions during Hurricane Katrina closely match the historic hydrographs measured during Hurricane Katrina and its immediate aftermath. Likewise, the modeled high water marks (HWM) closely match those measured in the aftermath of the storm.
- Scenario A1, *Katrina Actual Event Conditions*, resulted in maximum water surface elevation levels during Katrina at Plaintiffs' properties, reaching 10.5 ft at Adams; 10.7 ft at StBP #1; 10.8 ft at StBP #2; 11.0 ft at Tommaseo; 11.3 ft at StBP #3; 11.5 ft at StBP #4; 11.5 ft at Steve's RV; 11.5 ft at StBP #5; 11.6 ft at Bordelon; 11.7 ft at PSSI; and 17.3 ft at Florissant.

Principal Findings: *Impact of levee breaches (Scenario A2)*

- Flooding in the Lower Ninth Ward and vicinity up to Paris Rd. was dominated by the IHNC breaches.
- Flooding at locations behind the 40 Arpent levee to the east of Paris Rd. and within the Central Wetlands was dominated by the breaches of the Reach 2 levees. Thus, when the Reach 2 levee breaches are eliminated from the model, flooding levels at locations Adams, StBP #1, and StBP #2 were only moderately reduced by about 1.5 to 2.5 ft while locations to the east of Paris Rd. and within the Central Wetlands saw reductions of 3.9 to 7.7 ft. Florissant was not influenced.
- Scenario A2, *2005 MRGO/2005 Wetlands/IHNC Breaches Only*, resulted in maximum water surface elevation levels during Katrina at Plaintiffs' properties reaching 9.0 ft at Adams; 8.5 ft at StBP #1; 8.3 ft at StBP #2; 7.1 ft at Tommaseo; 6.2 ft at StBP #3; 4.6 ft at StBP #4; 4.6 ft at Steve's RV; 4.6 ft at StBP #5; 4.6 ft at Bordelon; 4.0 ft at PSSI; and 17.5 ft at Florissant.

Principal Findings: *Impact of wetlands and MRGO maintenance (Scenarios B1 and B2)*

- By defining the MRGO at its original completed dimensions and specifying 1956 wetland conditions, Scenario B1 demonstrates that the actual MRGO maintenance and wetland conditions only minimally impacted flooding in St. Bernard Polder, with maximum water surface elevations reducing by about 1 ft at all interior Polder locations and not at all at Florissant.
- Water levels along MRGO Reach 2 were minimally impacted while water levels in the central portion of the IHNC dropped by only 0.7 ft.
- Scenario B1, *MRGO as Designed/1956 Wetlands*, results in maximum water elevations during Katrina at Plaintiffs' properties reaching 9.3 ft at Adams; 9.5 ft at StBP #1; 9.7 ft at StBP #2; 10.1 ft at Tommaseo; 10.6 ft at StBP #3; 10.8 ft at StBP #4; 10.8 ft at Steve's RV; 10.8 ft at StBP #5; 10.9 ft at Bordelon; 11.0 ft at PSSI; and 17.2 ft at Florissant.
- Scenario B2, *MRGO as Designed/1956 Wetlands and IHNC breaches only*, results in maximum water elevations at Plaintiffs' properties reaching 8.0 ft at Adams; 7.5 ft at StBP #1; 7.5 ft at StBP #2; 6.3 ft at Tommaseo; 5.4 ft at StBP #3; 4.1 ft at StBP #4; 4.1 ft at Steve's RV; 4.1 ft at StBP #5; 4.1 ft at Bordelon; 3.8 ft at PSSI; and 17.3 ft at Florissant.

Principal Findings: *Impact of wetlands and MRGO construction (Scenario C)*

- Scenario C, the *No MRGO/1956 Wetlands* scenario, models conditions as they existed prior to 1958. This model indicates that while water levels in the central portion of the IHNC were lowered by about 1.4 ft, water levels in the vicinity of the MRGO Reach 1 at the Paris Rd. Bridge increased by about 0.3 ft. Thus, there was a 1.7 ft flood reduction for properties in the vicinity of the Lower Ninth Ward and little or no flood reduction elsewhere in the Polder.
- Scenario C, *No MRGO/1956 Wetlands*, resulted in maximum water elevations during Katrina at Plaintiffs' properties reaching 8.8 ft at Adams; 9.0 ft at StBP #1; 9.1 ft at StBP #2; 10.3 ft at Tommaseo; 11.0 ft at StBP #3; 11.5 ft at StBP #4; 11.5 ft at Steve's RV; 11.5 ft at StBP #5; 11.5 ft at Bordelon; 11.6 ft at PSSI; and 17.2 ft at Florissant.

Principal Findings: *Impact of the construction of federal levees (Scenario D)*

- Scenario D, which eliminates the key federal levees, shows that the water from Lake Borgne essentially flows unimpeded into the Central Wetlands and then easily overtops the 40 Arpent levee as well as the levees protecting Poydras, LA and St. Bernard, LA.
- This model demonstrates that without the federal levee system, flooding at interior Polder locations increased by 3 to 5 ft. Flooding at Florissant remained the same as in all cases.
- Scenario D, *No Federal Levees/2005 MRGO/2005 Wetlands*, resulted in maximum water elevations during Katrina at Plaintiffs' properties reaching 14.1 ft at Adams; 14.3 ft at StBP #1; 14.5 ft at StBP #2; 14.7 ft at Tommaseo; 15.0 ft at StBP #3; 15.6 ft at StBP #4; 15.6 ft at Steve's RV; 15.8 ft at StBP #5; 16.8 ft at Bordelon; 14.8 ft at PSSI; and 17.1 ft at Florissant.

Principal Findings: *Impact of the construction of federal levees, construction of the MRGO, and deterioration of the wetlands (Scenario E)*

- Scenario E eliminates the key federal levees and the MRGO, and considers the wetlands to be in their 1956 condition. This model again shows that the water from Lake Borgne essentially flows unimpeded into the Central Wetlands and then easily overtops the 40 Arpent levee as well as the levees protecting Poydras, LA and St. Bernard, LA. Flooding at interior Polder locations increased by 3 to 5 ft and flooding at Florissant remained the same as in all cases.
- Since the water comes from Lake Borgne and is pushed into the Polder unimpeded, the conditions of the wetlands and channels were only of minor consequence.
- Scenario E, *No Federal Levees/No MRGO/1956 Wetlands*, resulted in maximum water elevations during Katrina at Plaintiffs' properties reaching 13.8 ft at Adams; 14.1 ft at StBP #1; 14.3 ft at StBP #2; 14.5 ft at Tommaseo; 14.9 ft at StBP #3; 15.5 ft at StBP #4; 15.6 ft at Steve's RV; 15.7 ft at StBP #5; 16.6 ft at Bordelon; 14.9 ft at PSSI; and 16.9 ft at Florissant.

Principal Findings: *Summary of peak water levels for seven scenarios*

- **Scenarios A1, A2, B1, B2, C, D, and E** peak water levels at Plaintiff's properties (in ft relative to NAVD88 2004.65) for all seven scenarios are summarized in the Table below.

Location	Scenario A1	Scenario A2	Scenario B1	Scenario B2	Scenario C	Scenario D	Scenario E
Adams	10.5	9.0	9.3	8.0	8.8	14.1	13.8
SBP #1	10.7	8.5	9.5	7.5	9.0	14.3	14.1
SBP #2	10.8	8.3	9.7	7.5	9.1	14.5	14.3
Tommaseo	11.0	7.1	10.1	6.3	10.3	14.7	14.5
SBP #3	11.3	6.2	10.6	5.4	11.0	15.0	14.9
SBP #4	11.5	4.6	10.8	4.1	11.5	15.6	15.5
Steve's RV	11.5	4.6	10.8	4.1	11.5	15.6	15.6
SBP #5	11.5	4.6	10.8	4.1	11.5	15.8	15.7
Bordelon	11.6	4.6	10.9	4.1	11.5	16.8	16.6
PSSI	11.7	4.0	11.0	3.8	11.6	14.8	14.9
Florissant	17.3	17.5	17.2	17.3	17.2	17.1	16.9

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Expert Background and Qualifications

- I am the Joseph and Nona Ahearn Endowed Professor in Computational Science and Engineering and the Henry J. Massman Chairman of the Department of Civil & Environmental Engineering & Earth Sciences at the University of Notre Dame. I have concurrent appointments in the Department of Applied and Computational Mathematics and Statistics and the Department of Computer Science and Engineering.
- I earned my B.S. (1979) and M.S. (1981) degrees in Civil Engineering at the State University of New York at Buffalo and Ph.D. (1984) degree in Civil Engineering, specializing in hydrodynamics, from the Massachusetts Institute of Technology.
- My research focuses on the development, analysis and application of coastal ocean and estuarine hydrodynamic, constituent transport and sediment transport codes and models. This encompasses the development of the basic algorithms; theoretical analysis of algorithm behavior; development of high performance codes in vector and parallel computing environments; linkages to wave and weather models; and verification and validation.

Expert Background and Qualifications

- I am the co-developer of the widely used ADCIRC finite element coastal circulation code. ADCIRC is a robust, efficient and accurate analysis, design, and forecast code that is used by universities, the U.S. government, and private sector companies worldwide.
- I have modeled circulation, waves, and sediment transport in oceans, continental shelves, estuaries, rivers, coastal flood plains and lakes. Regions I have or am now currently studying include the North Sea, Massachusetts Bay, Boston Harbor, the Western North Atlantic Ocean, the Gulf of Mexico, the Caribbean Sea, the eastern and central Pacific Ocean, the Indian Ocean, the South China Sea, the coasts of Mississippi, Louisiana, Texas, Alabama, Florida, New York, Washington, Oregon, Alaska, and the island of Puerto Rico, the U.S. Virgin Islands, and the Hawaiian Islands.
- My laboratory is at the forefront of developing ultra-high resolution unstructured grid multi-physics, multi-scale computer models for the coastal ocean, and successfully transitioning these models for design and analysis of flood control and environmental impact assessment projects.

Expert Background and Qualifications

- My work has been subject to thorough peer review and I have published extensively in leading journals including *Journal of Geophysical Research, Monthly Weather Review, Proceedings of the National Academy of Sciences of the United States of America, Computer Methods in Applied Mechanics and Engineering, Advances in Water Resources, Weather and Forecasting, Journal of Applied Meteorology and Climatology, Ocean Modelling, Journal of Computational Physics, Coastal Engineering, Journal of Hydraulic Engineering, Journal of Waterway, Port, Coastal, and Ocean Engineering, Natural Hazards, Continental Shelf Research, Journal of Scientific Computing, Geophysical Research Letters, International Journal for Numerical Methods in Fluids, Physics Today, Marine Technology Society Journal, Tellus, Journal of Hydraulic Research, Journal of Physical Oceanography, International Journal for Numerical Methods in Engineering,* and *Review of Geophysics.*

Expert Background and Qualifications

- I have worked in Louisiana for over two decades and my work and models have been and continue to be the basis for all the Louisiana coastal flood modeling work by FEMA, the U.S. Army Corps of Engineers, and the State of Louisiana. My codes and models are also used by National Oceanic and Atmospheric Administration (NOAA) for forecasting and are required to be used by the Nuclear Regulatory Commission for nuclear power station design.
- I was a team co-lead in the U.S. Army's IPET investigation of the Katrina flooding failures in Louisiana and led the subsequent model development efforts for the evaluation of flood mitigation systems and risk assessment in Louisiana and Texas for the U.S. Army Corps of Engineers and FEMA.
- I have served as a commissioner on the Southeast Louisiana Flood Protection Authority from 2007 through 2012 appointed by Governors Kathleen Blanco and Bobby Jindal.
- I served as an advisor for the UNESCO Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology on Enhancing Forecasting Capabilities for North Indian Ocean Storm Surges.

Expert Background and Qualifications

- I have also served as an expert in previous litigation related to Hurricane Katrina, including *Robinson v. United States* 06-cv-2268 *(E.D. La.)* where my models were applied by both plaintiffs and the United States.
- My laboratory is also focused on teaching and mentoring both undergraduate and graduate students, with lab members having been awarded 17 outstanding teacher and teaching assistant awards. I also co-lead an annual field trip for our undergraduates that visits large infrastructure projects, and co-organize the *Challenges and Innovation Lecture Series in Civil and Environmental Engineering* which exposes students to and encourages interaction with world leaders from industry, government and academia. I am the faculty advisor for the Notre Dame chapter of *Engineers without Borders*.
- My former graduate students and post docs are in academia, government, and industry, and continue to work in leading positions in coastal and hurricane related studies.

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ADCIRC Models: *ADCIRC code to solve for water levels and currents*

- **ADCIRC** is a computer code that solves for water surface elevations – *or surge in the case of a hurricane* - and currents in two and three dimensions.
- The **ADCIRC** code solves partial differential equations that express fundamental physical laws: ***conservation of momentum* (F=ma) *and conservation of water volume***.
- **ADCIRC** accounts for tidal, riverine, wind, atmospheric pressure, wind waves, and water density driven processes in the coastal ocean and the interaction with the basin and regional bathymetry/topography, geometry, and surface and bottom roughness, or friction.
- **ADCIRC** has been developed jointly by faculty at the University of Notre Dame, the University of North Carolina at Chapel Hill, and the University of Texas at Austin. It has evolved into a community code.
- The **ADCIRC** code works together with user defined ***unstructured grids*** and supplemental data that describe the geometry, bathymetry, topography, features, and roughness of the physical system.
- The **ADCIRC** code is a state of the art code that takes superb advantage of high performance massively parallel computer platforms, allowing users to apply high resolution grids in order to improve accuracy.

ADCIRC Models: *SWAN code to solve for ocean and nearshore waves*

- **SWAN** is a computer code that solves for wind waves in the ocean.
- Waves are driven by winds, and are strongly influenced by the systems' bathymetry/topography, geometry, and surface roughness, as well as water column depths and currents.
- **SWAN** simulates waves by solving a partial differential equation for a variable related to wave energy. The code describes the generation, propagation, transformation, and dissipation of wind waves.
- The **SWAN** code has been developed by Delft University of Technology, a leading technical university in Europe renowned for its expertise in coastal engineering.
- A ***grid*** with supplemental data is used to inform the **SWAN** code of the geometry, bathymetry, topography, features and roughness of the physical system being modeled
- The **SWAN** code has recently been modified to work with ***unstructured grids***.
- The ***unstructured grid*** version of **SWAN** uses **ADCIRC's** parallel computing infrastructure in order to achieve superb performance on massively parallel high performance computers.

ADCIRC Models: *SWAN+ADCIRC codes to solve for coupled waves, water levels and currents*

- **SWAN+ADCIRC** is a coupled code that allows the interaction of wave and current processes *(Dietrich et al., 2011b; Dietrich et al., 2012).*
- The **SWAN+ADCIRC** code computes wind driven waves, water surface elevations, and currents simultaneously.
- **ADCIRC** and **SWAN** interact
  - **ADCIRC** water levels and currents affect **SWAN** waves
  - **SWAN** derived wave breaking forces **ADCIRC** water level setup and currents
- The combined code uses the identical ***unstructured grid*** and operates superbly on high performance parallel computing systems.
- **SWAN+ADCIRC** is a joint code development project between Delft University, the University of Notre Dame, the University of North Carolina at Chapel Hill, and the University of Texas at Austin and was funded through the U.S. Office of Naval Research.

ADCIRC Models: *Grids and resolution*

- The geographic system is described to the **SWAN+ADCIRC** codes using the ***unstructured grid*** consisting of vertex grid points that connect triangular finite elements. Topography, bathymetry, and frictional resistance are specified at the ***grid points***. The waves, water levels, and currents are also computed at the ***grid points***.
- The resolution of a ***grid***, *i.e.*, the spacing of the grid points, determines how accurately the physical system is represented, as well as how accurately the waves, water surface elevations, and currents are computed.
- The **SWAN+ADCIRC** codes operate on ***unstructured grids*** with variable resolution, with the finest grid resolution provided where the physical system and/or waves, water surface, and/or currents change rapidly.
- The **SWAN+ADCIRC** codes + ***unstructured grids*** + ***supplemental data*** = ***" the model"***.

ADCIRC Models: *Grids and resolution*

- *Grid* resolution is conceptually similar to pixilation of a digital photograph where increases in the density of the pixels result in a much finer representation of the image.
- Higher resolution better reflects the physical conditions of a coastal region, and facilitate more accurate modeling.
- A portion of the **SL16** ***unstructured grid*** in Southeastern Louisiana and metropolitan New Orleans and vicinity is shown Figure 2 on the next slide. The ***grid*** is made up of triangles connected with vertices or ***grid points*** where bathymetry and friction coefficients are defined and water surface elevation, currents, and wave characteristics are computed.
- It is noted that the density of the ***grid*** increases dramatically in the nearshore and inland areas as well as in the channels to the point that the triangles of no longer discernible at these figure scale.
- A very high level of grid resolution is applied in the **SL16** ***grid***.

ADCIRC Models: *Grids and resolution*

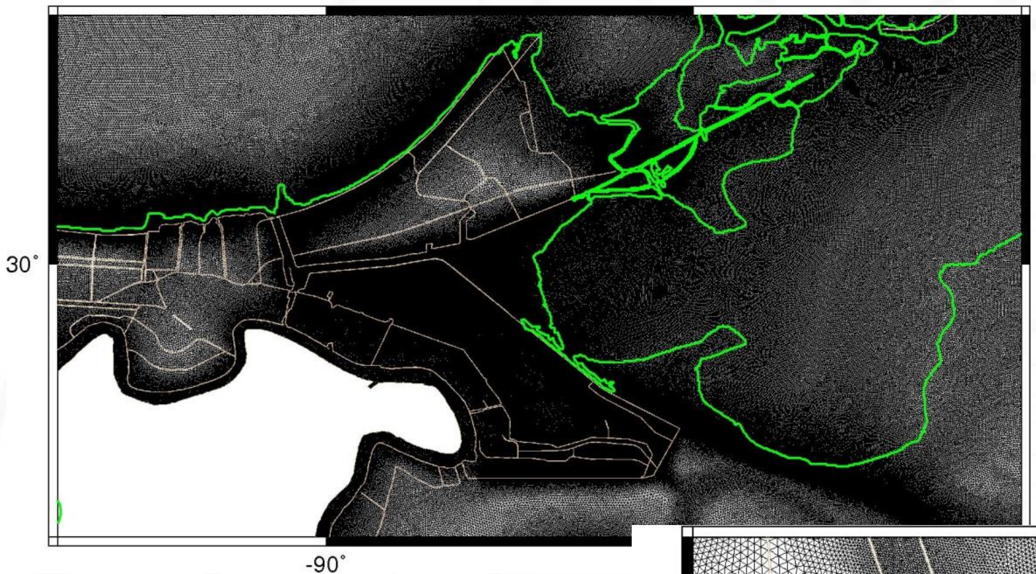

Figure 2a

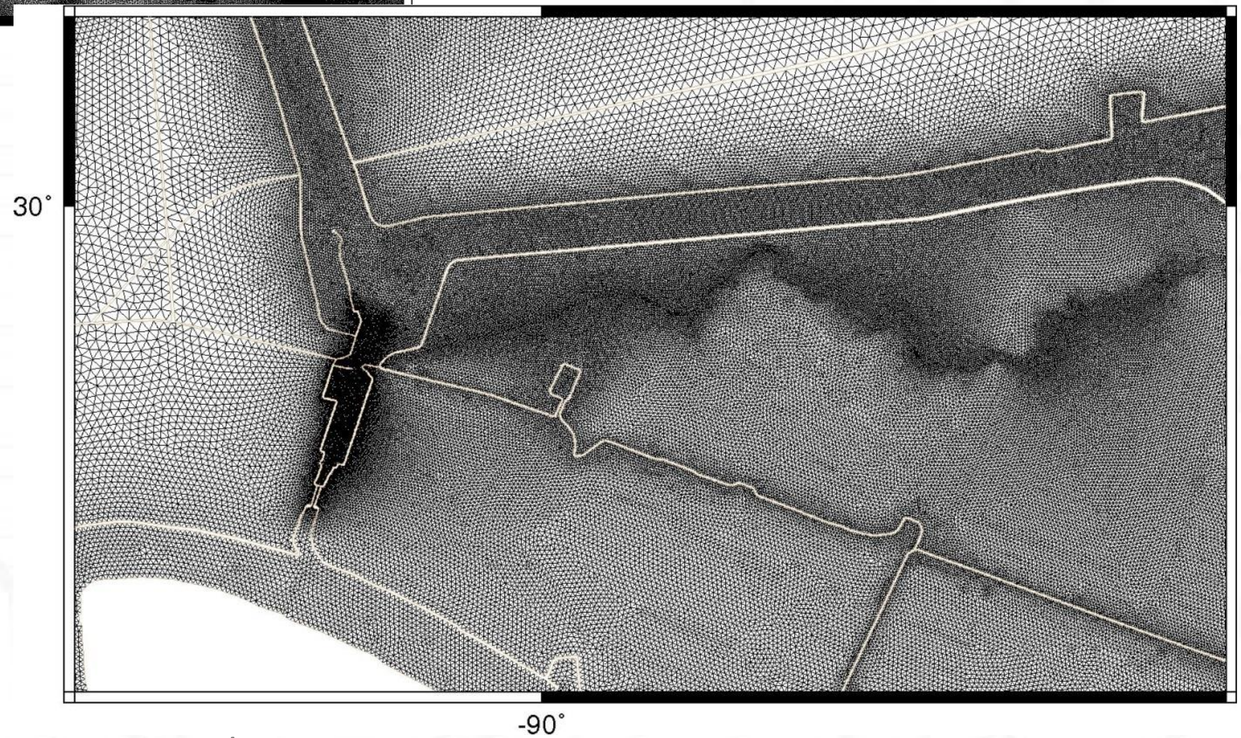

Figure 2b

ADCIRC Models: *Verification, validation, and external peer review*

- The **ADCIRC** and **SWAN+ADCIRC** codes and models have been subject to extensive verification (demonstrating that the governing equations are being solved correctly) and validation (demonstrating that the tidal, riverine, wind and wind wave driven computed water surface elevations and currents correctly represent the measured responses).
- The **ADCIRC**, **SWAN** and **SWAN+ADCIRC** codes and the modeling methodologies have been subject to international academic peer review through extensive publication in leading journals, through international adoption by government, industrial, consulting, and academic sectors, as well as through the National Academies and American Society of Civil Engineers external reviews *(Westerink et al., 2008; Bunya et al., 2010; Dietrich et al., 2010a; Dietrich et al., 2011a; Dietrich et al., 2011b; Kennedy et al., 2011; Dietrich et al., 2012; Hope et al., 2013; Kerr et al., 2013a; 2013b)*.

ADCIRC Models: *Verification, validation, and external peer review*

- A recent NOAA Integrated Ocean Observing System ("IOOS") study has shown that the **SWAN** and **ADCIRC** codes and models are leaders in accurate hindcasting of hurricane storm surge and wave environments and, in fact, represent a huge advance over the SLOSH model used in hurricane surge forecasting by the National Weather Service (Kerr et al., 2013b)
- This is particularly the case when the **SWAN** and **ADCIRC** models are applied with high resolution ***unstructured grids*** *(Hope et al., 2013; Kerr et al., 2013a).*

ADCIRC Models: *Worldwide applications*

- **ADCIRC** models are used and applied throughout the world by governments, academia, and the private sector to analyze storm surge, evaluate risk, and design flood control infrastructure.
- **ADCIRC** models are used and applied by:
  - the Federal Emergency Management Agency (FEMA) to develop Flood Insurance Rate Maps *(FIRMS)* along the U.S. Atlantic and Gulf coasts;
  - the U.S. Army Corps Engineers to design the new Hurricane and Storm Damage Risk Reduction System in metropolitan New Orleans;
  - the Nuclear Regulatory Commission which requires **ADCIRC** studies to evaluate the safety of U.S. coastal nuclear power stations;
  - NOAA to forecast tides and extra-tropical storms along the East and Gulf coast of the United States; ***http://www.opc.ncep.noaa.gov/estofs/estofs_surge_info.shtml***
  - NOAA to analyze for tides in Vertical Datum projects;

ADCIRC Models: *Worldwide applications*

- **ADCIRC** models are used and applied by:
  - NOAA to develop an up-to-date hurricane forecasting model;
  - the government of South Korea to design and operate tidal power plants;
  - FMGlobal, a large industrial mutual insurance company to evaluate the flooding associated with Hurricane Sandy in New York City and to evaluate hurricane induced flood risk in China and Korea;
  - the State of Hawaii to help forecast and evaluate risk from hurricanes;
  - the State of Alaska to help forecast storms and understand coastal storm risk;
  - the Indian National Centre for Oceanic Information Services to evaluate storm surge in India;
  - the City of New York to evaluate proposed regional and local coastal flood protection measures for the *2013 New York City Special Initiative for Rebuilding and Resiliency*

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ADCIRC Models for Southern Louisiana: *Model evolution*

- Hurricane wave and surge model skill depends on the level of ***grid resolution***, how well the model reflects the physical attributes of a coastal area, and how accurately winds, air-sea drag, bottom roughness, and wave-current interaction are quantified.
- Through my work and the work of others in the field, a sequence of **ADCIRC** and **SWAN+ADCIRC** models of increasing detail and complexity has evolved over the past decade. These models have continuously improved on both the level of ***grid resolution***, *i.e.* how well they describe the physical system (topography, bathymetry, and surface roughness), and on their descriptive physics (wave-current interaction, air-sea drag, and bottom roughness).
- Particularly in coastal Louisiana, where a recent series of powerful hurricanes, beginning with Katrina, drew the intense focus of the **ADCIRC** modeling community, we have worked to perfect a ***high resolution grid***, and to improve our understanding of the underlying physics and geographic features that influence storm surge, waves and currents in the region.

ADCIRC Models for Southern Louisiana: *Model evolution*

- Beginning with the original **ADCIRC** model for Southern Louisiana ("**S08**"), which I developed for the United States Army Corps of Engineers New Orleans District a decade ago, and which was used by Plaintiffs' expert Dr. Kemp in this case and in *In re: Katrina Canal Breaches Consolidated Litigation*, No. 05-4182 (E.D. La.) ("*Robinson*"), I have worked to refine the **ADCIRC** code and ***grids*** and supplemental input data to more accurately model hurricane storm surge in this region (Westerink et al., 2008).
- A series of "**SL15**" models developed following Hurricane Katrina incorporated much greater ***grid resolution*** to describe the geographic, topographic (now based on LiDAR), bathymetric, and land cover detail in both Louisiana and Mississippi. The **SL15** ***grid*** applied 2,511,009 grid points compared to 314,442 grid points in the **S08** model. This improved ***grid*** in its highest resolution areas allowed the model to capture points 65 ft apart – as opposed to 320 ft apart in **S08**.
- The **SL15** models also integrated much better descriptions of the physics by including **WAM** and **STWAVE** structured grid wave modeling, land cover based Manning's *n* descriptions of friction, and a limited air-sea drag law *(Bunya et al., 2010; Dietrich et al, 2010a).*

ADCIRC Models for Southern Louisiana: *State of the art SL16 model*

- For my analysis in this case I used the most recent **SL16** model, which reflects the current state-of-the-science
  - The operational **SL16** ***grid*** is comprised of 5,036,960 grid points and 9,949,3167 triangular elements with resolution as high as 45 ft
  - The model captures a very high level of geometric, topographic, and bathymetric detail as supported by the high level of resolution in the grid
  - The model further refines channels and rivers, better resolves the surf zone where wave breaking takes place, and improves the definition of topography in wetlands by applying USGS land use type maps
- The **SL16** model is designed to work with the **SWAN+ADCIRC** code and integrally couples the wave-current interaction – an improvement over prior models in which the wave modeling (using **WAM** and **STWAVE** wave models) was performed loosely and on a structured "nested" grid.
- The **SL16** model also incorporates a more accurate representation of bottom friction on the continental shelf, and applies a much improved air-sea interaction model based on direct measurements obtained using GPS instrumented dropsondes released from NOAA's hurricane hunter planes.

ADCIRC Models for Southern Louisiana: *Validation of the SL16 model*

- The SWAN+ADCIRC **SL16** and associated models have been validated in several studies published in leading peer reviewed journals *(Dietrich et al., 2011a; Dietrich et al., 2012; Hope et al., 2013; Kerr et al., 2013a).*
- In these studies, performed in the course of academic research and outside the context of litigation, the **SL16** model was used to hindcast the storm surge and waves experienced in coastal Louisiana during Hurricanes Katrina, Rita, Gustav, and Ike.
- The later hurricanes produced extensive high quality wave and surge data due to hardening of existing gauges and deployment of additional permanent and event gauges.
- Measured against the actual high water marks (HWM) and peak high water from hydrographs recorded during these storms, the **SL16** model produced maximum water elevations with average absolute error rates of 0.6 ft.
- These **SL16** hindcasts also achieved a 95% HWM confidence interval of 1.5 ft for these storms, indicating that one can expect 95% of the high water marks to be within 1.5 ft.

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SL16 Model Applied to St. Bernard Polder: *Model refinements*

- For the purposes of my study and analysis for this case, I refined the **SL16** ***grid*** and model to focus detailed attention on the specific geographic region of interest.
- To that end, I modified the **SL16** grid to include even more resolution in the IHNC, and eliminated the portion of the SL16 grid that represents inland features west of the Mississippi River which were not inundated during Hurricane Katrina.
- The refinements reduced computer simulation time and cost, and also permitted me to add greater definition to the bathymetric, topographical and frictional characteristics featured in the IHNC portion of the model.
- The domain and regional topography and bathymetry used for my study in this case is shown in Figures 3 and 4. The resolution of the grid is apparent in these figures, showing that channels are particularly highly resolved.
- Figure 5 shows the spatial distribution of a frictional parameter known as Manning's *n*, a standard way in hydraulic analysis of indicating how much resistance the land surface exerts on flow or, in other words, how much "bottom friction" limits flow.

SL16 Model Applied to St. Bernard Polder: *Domain and bathymetry*

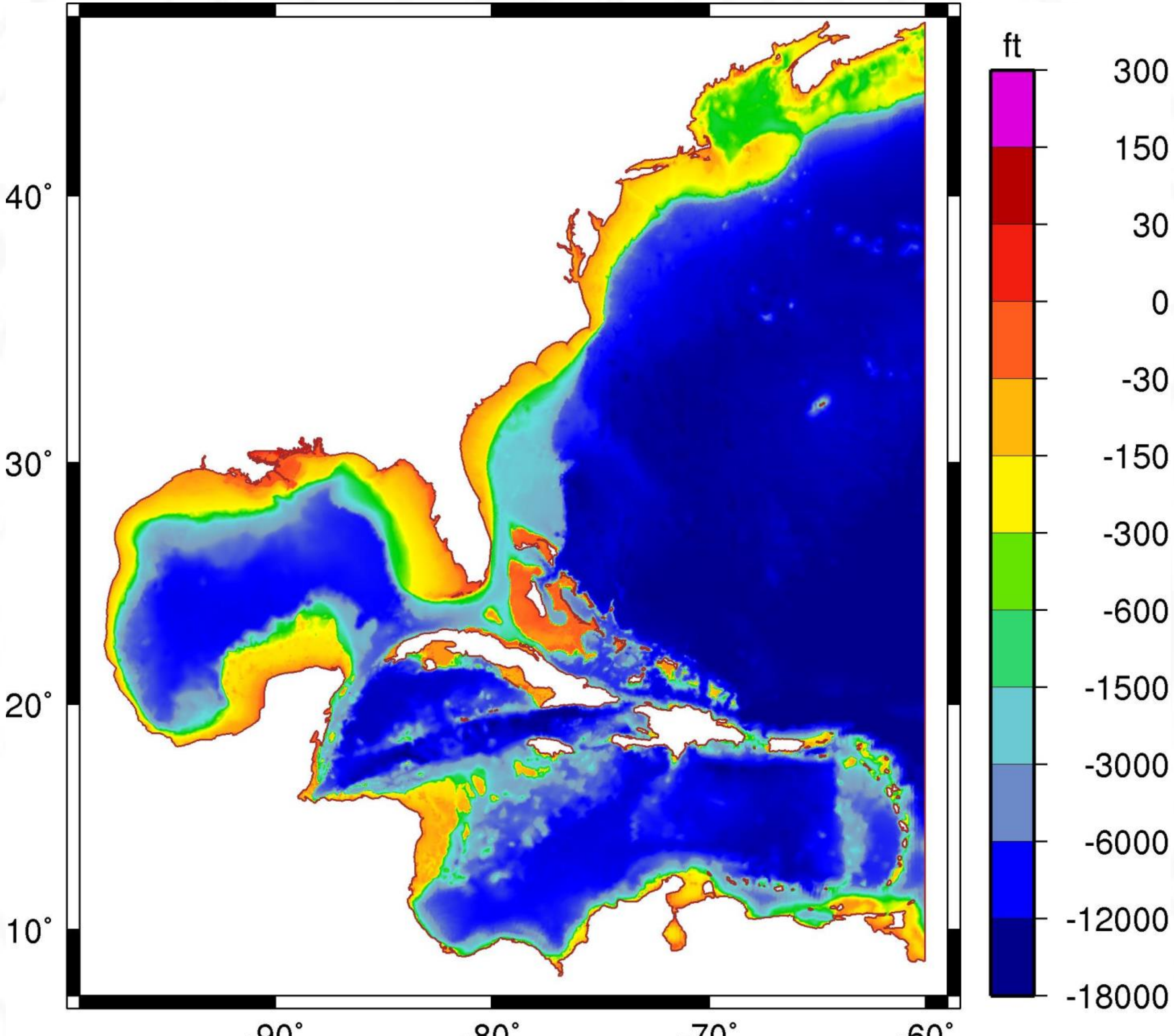

Figure 3

SL16 Model Applied to St. Bernard Polder: *Regional topography and bathymetry*

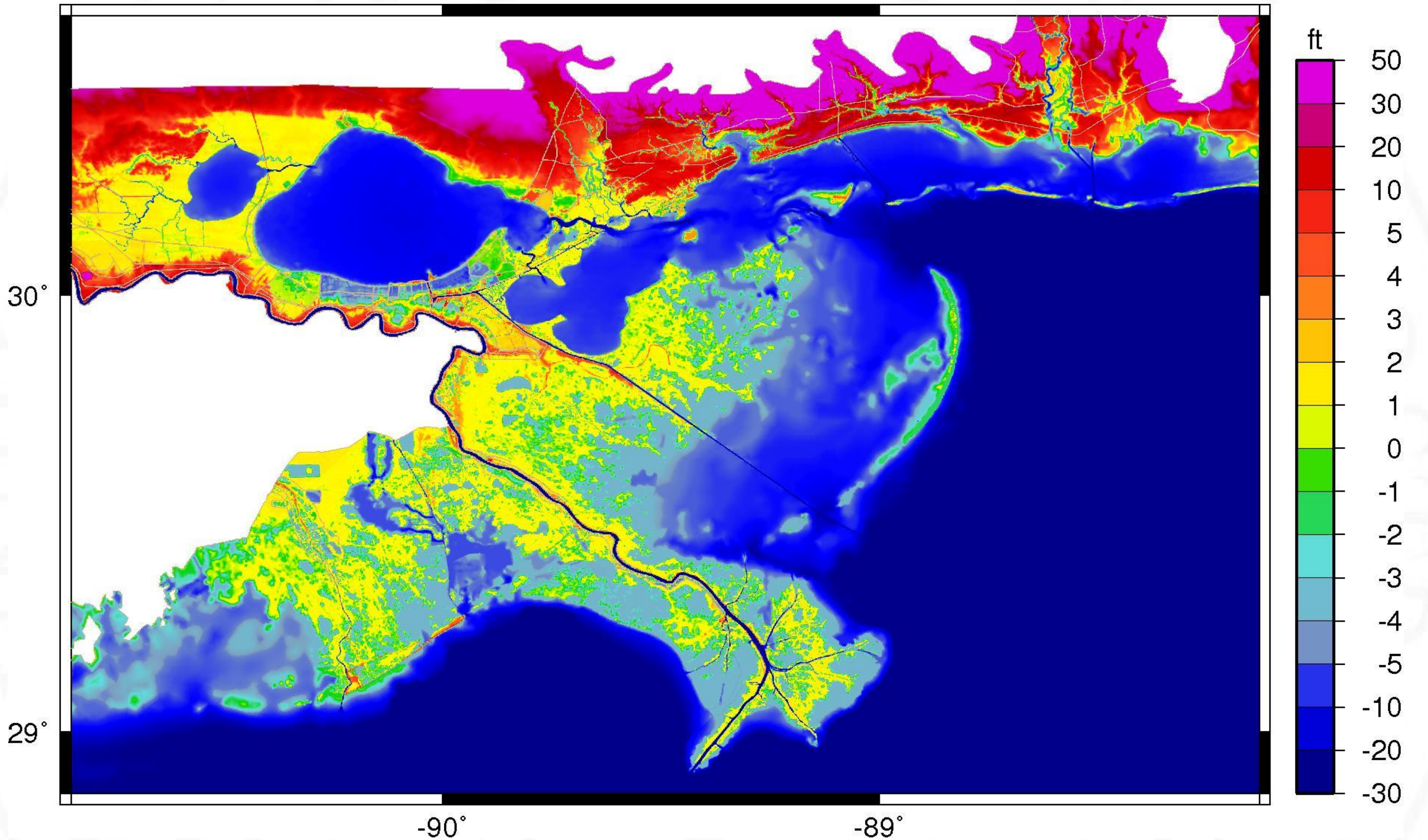

Figure 4

SL16 Model Applied to St. Bernard Polder: *Regional friction (Manning's n parameter)*

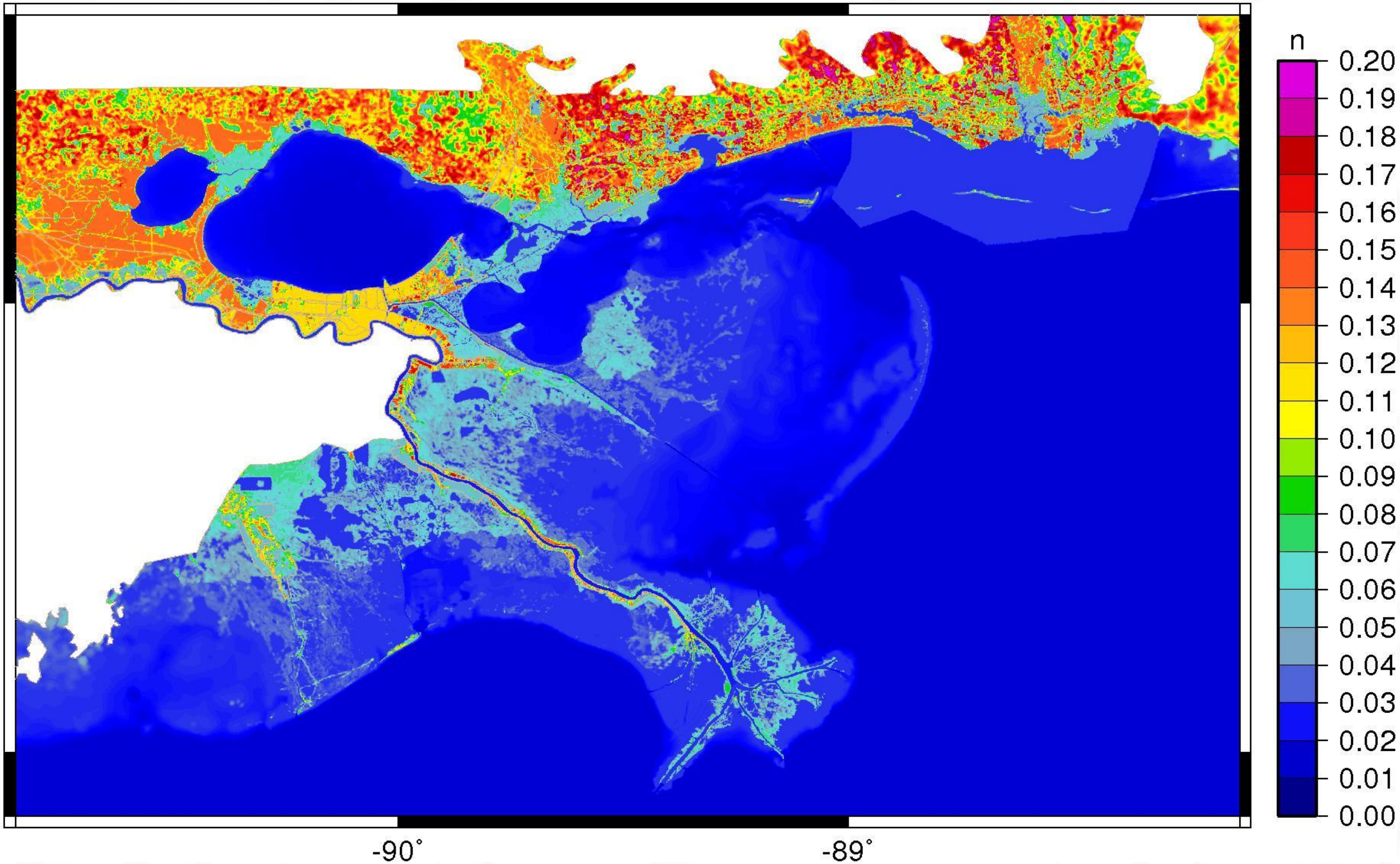

Figure 5

SL16 Model Applied to St. Bernard Polder: *Improved local resolution*

- Among the refinements to the grid include resolution improvements in the physical representation of the IHNC.
- In previous **ADCIRC** models, including the **SL15** model I used to simulate Hurricane Katrina flooding in the *Robinson* trial, we focused our attention upon resolving the bathymetry and dimensions of the MRGO Reach 2, and achieved a high degree of accuracy in modeling that channel. Those improvements carried forward into the **SL16** grid used here.
- For this study, we added more resolution and geographic detail in the IHNC to bring the physical representation of that channel in line with the prior improvements to MRGO Reach 2.
- Figure 6 shows the highly resolved bathymetry and topography in the IHNC and the highly resolved geographical features in St. Bernard Polder and its immediate local surroundings.
- Figure 7 shows the Manning's *n* frictional parameter applied to St. Bernard Polder and its immediate local surroundings.

SL16 Model Applied to St. Bernard Polder: *Study area topography and bathymetry*

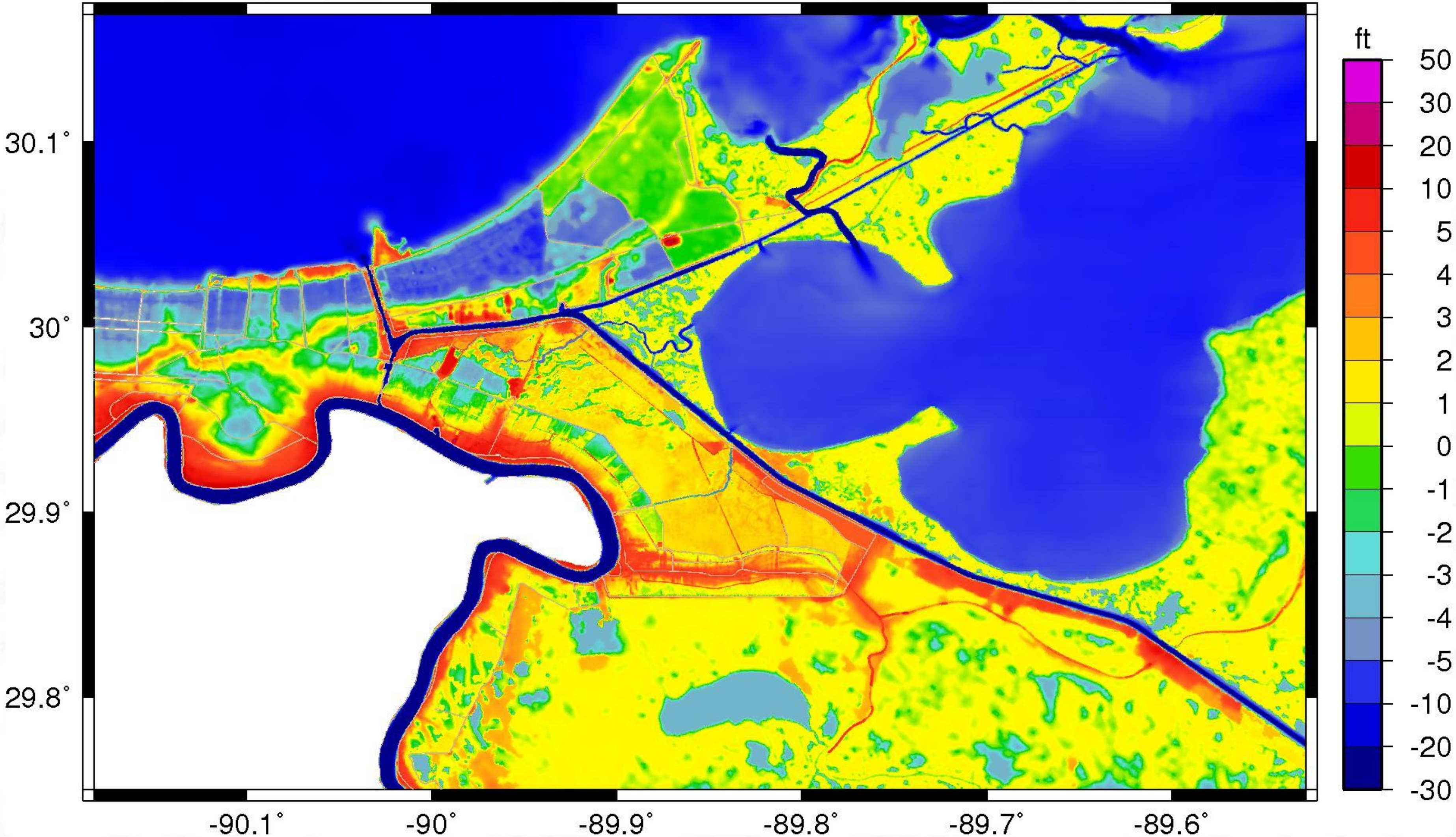

Figure 6

SL16 Model Applied to St. Bernard Polder: *Study area friction (Manning's n parameter)*

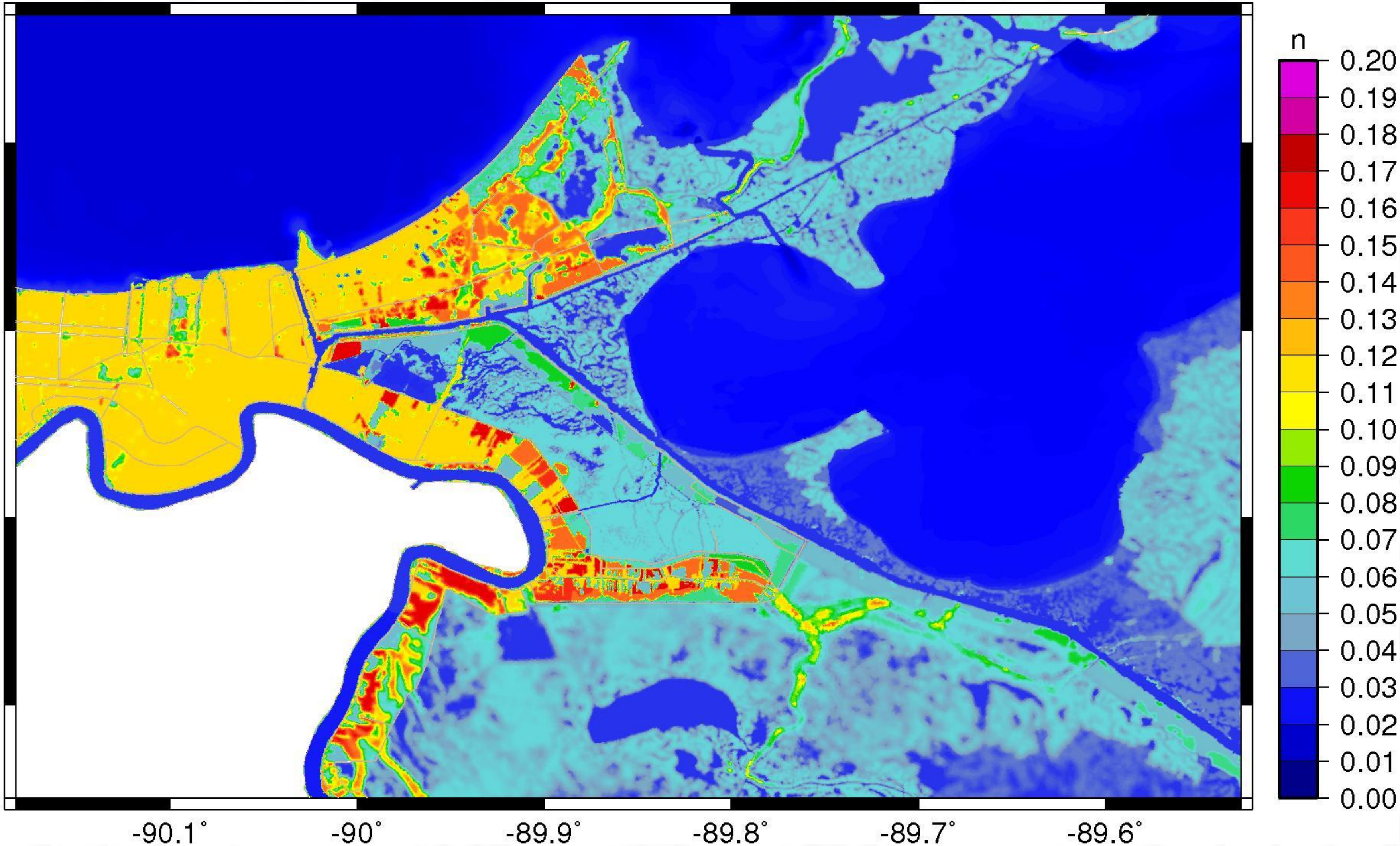

Figure 7

SL16 Model Applied to St. Bernard Polder: *Improved local resolution*

- Figure 8 shows the highly resolved bathymetry and topography within St. Bernard Polder, with each Trial Property labeled to depict its location within the Polder.
- Figure 9 shows the Manning's *n* frictional parameter applied within St. Bernard Polder, with each Trial Property labeled to depict its location within the Polder.
- The 2316 Florissant Property is situated outside the federal levee system, and is not depicted in these two local figures.

SL16 Model Applied to St. Bernard Polder: *Western St. Bernard Polder topography and bathymetry*

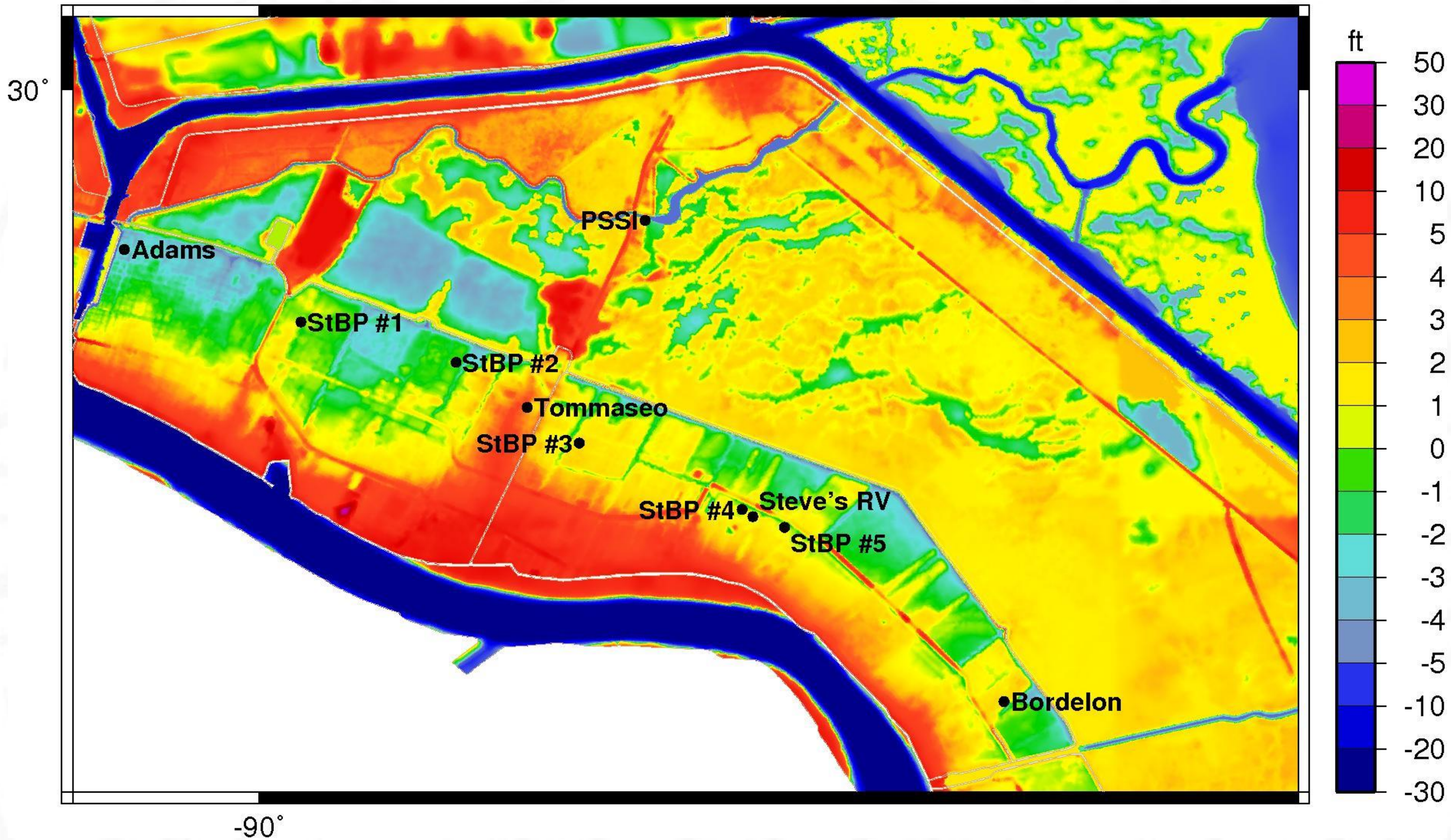

Figure 8

SL16 Model Applied to St. Bernard Polder: *Western St. Bernard Polder friction (Manning's n parameter)*

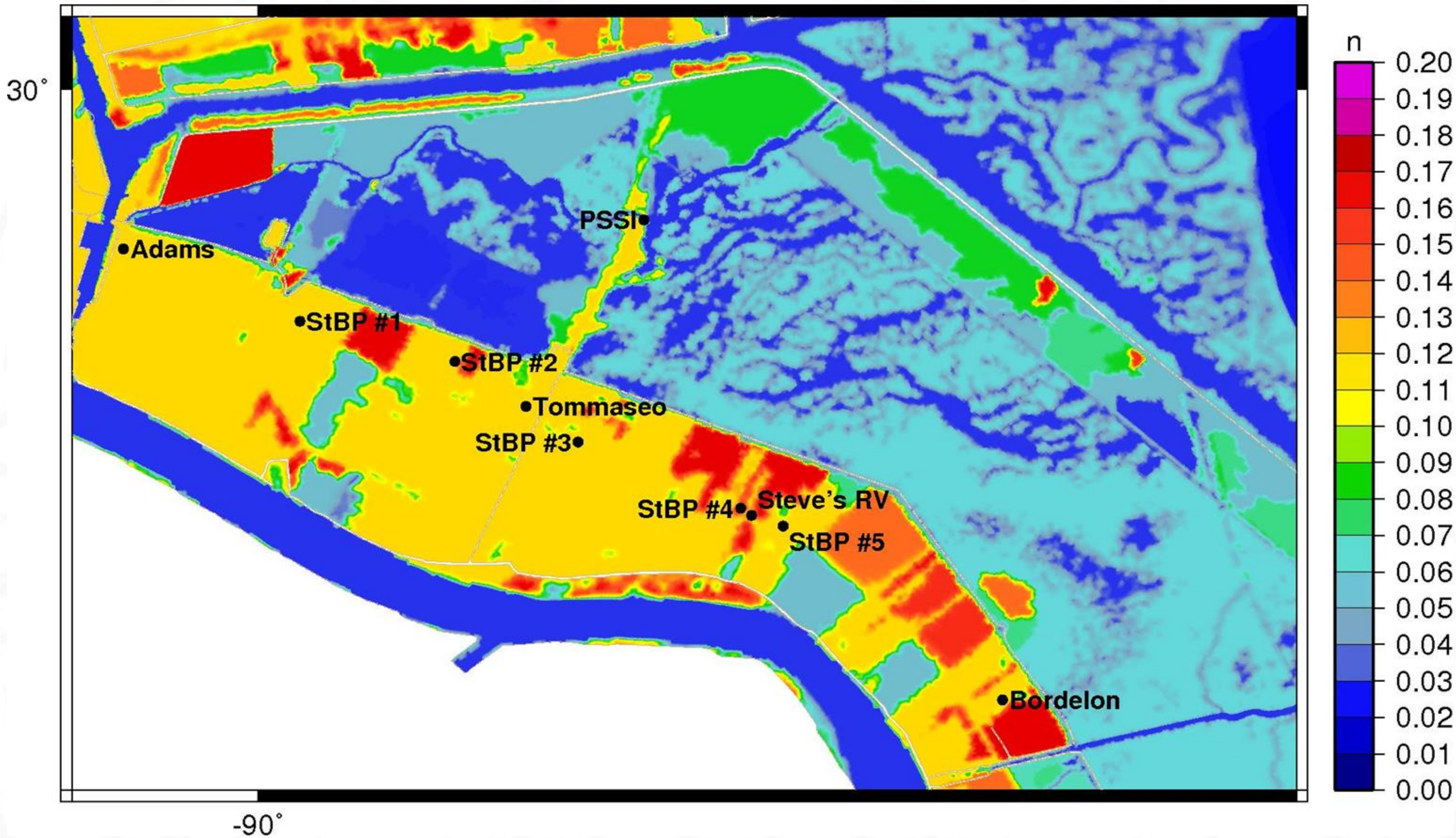

Figure 9

SL16 Model Applied to St. Bernard Polder: *Implementing levee breaches*

- For this study, I also incorporated into the model levee degradation that occurred in various places along St. Bernard Polder's exterior perimeter defenses during the storm.
- My modeling includes the two major breaches along the IHNC, known as the IHNC North breach and the IHNC South breach.
- I also modeled the numerous breaches along the LPV levees running parallel to MRGO Reach 2.
- The breach locations depicted in Figure 10, which shows in red locations of these breaches.

SL16 Model Applied to St. Bernard Polder: *implementing levee breaches*

- Study Area breaches in St. Bernard Polder levees are indicated with red lines. Numbered Plaintiff Properties are indicated with yellow diamonds and numbers.

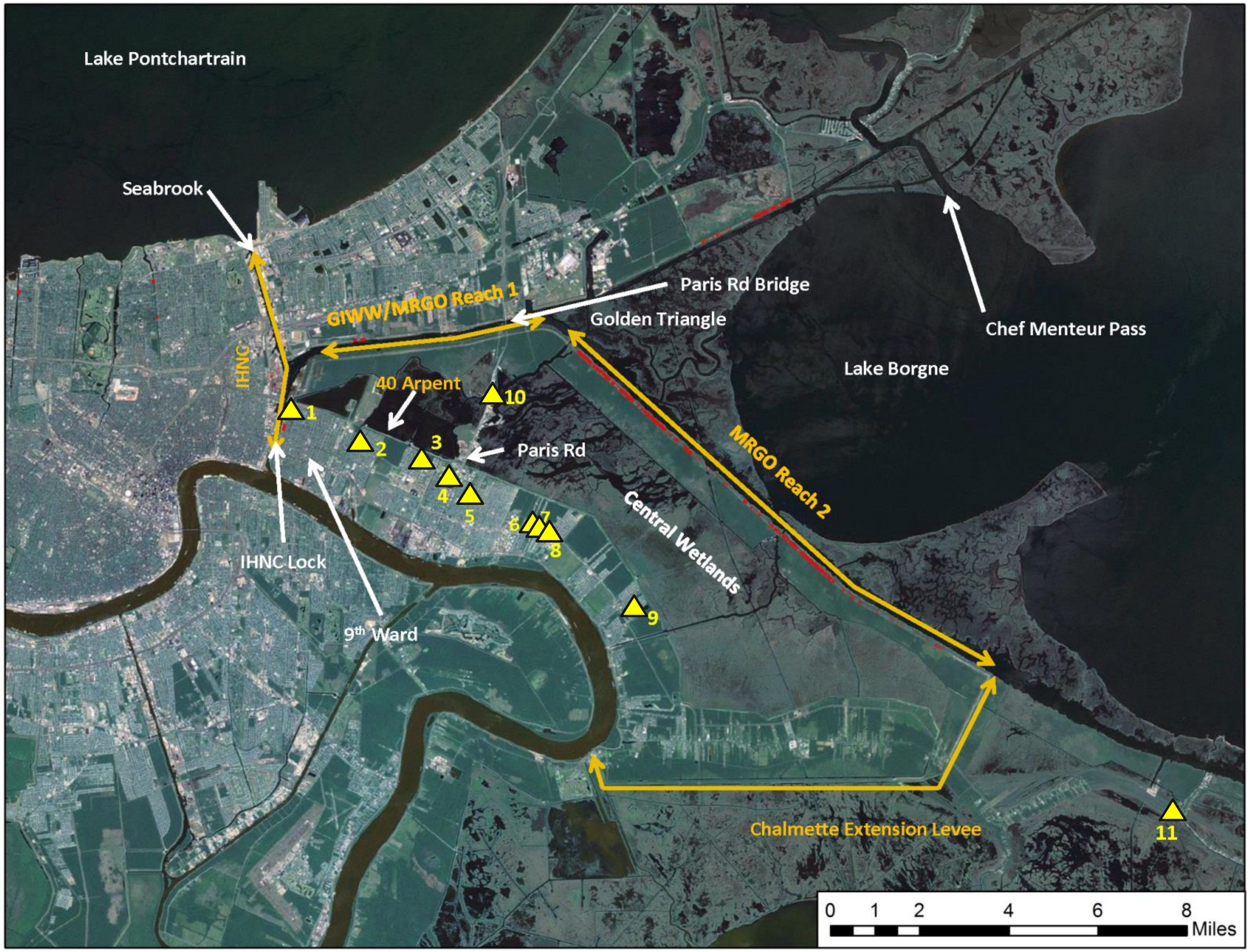

Figure 10

SL16 Model Applied to St. Bernard Polder: *Implementing levee breaches*

- **ADCIRC** employs standard levee and weir overtopping formulae used in hydraulic engineering practice.
  - These formulae have been extensively used in **ADCIRC** to overtop levees.
- In this application, I used a time-varying levee crest to simulate the deterioration of the levees.
- The breach times and durations were specified in a manner consistent with the consensus that has developed among other hydrodynamic modeling experts who have approached this task in studying the flooding during Hurricane Katrina including:
  - Professor Robert A. Dalrymple in an expert report prepared for a non-United States defendant in *Armstrong v. United States*, 10-cv-866 (E.D. La)
  - Dr. M. M. Aalberts Kok in expert reports prepared in 2007 and 2008 for Plaintiffs in *Robinson v. United States,* No. 05-4182 (E.D. La.)
- In this application, I used weir coefficients appropriate to the shape of the levee (wall versus smooth crested earthen levee) and to the state of the levee (in tact versus degraded).

SL16 Model Applied to St. Bernard Polder: *Implementing levee breaches*

- The IHNC North breach was initiated at 6 am on August 29 and developed to the full breach depth over a 30 minute duration.
- The IHNC South breach was initiated at 6:45 am and developed to the full breach depth over a 15 minute duration.
- The MRGO Reach 2 breaches were initiated at 5:45 am and developed to the full breach depths over a 2.5 hour duration
  - As discussed, the timing and duration of the MRGO Reach 2 breaches modeled here are consistent with those adopted by the Plaintiffs' expert Dr. Kok in the *Robinson* case, who modeled breaching of the MRGO Reach 2 levees from 5:00 am to 8:30 am on August 29, 2005.
- However, I am not a geotechnical expert and express no opinion on the precise physical manner in which the Reach 2 levees failed, or upon the MRGO's alleged role in causing those levees to degrade.

SL16 Model Applied to St. Bernard Polder: *Wave overtopping*

- I also computed wave overtopping through a module based on the *EurOtop* formula, which uses wave conditions at the levee in order to compute wave overtopping flows into St. Bernard Polder *(Pullen et al. 2007).*
- The wave overtopping calculations incorporate **ADCIRC** water levels, **SWAN** wave heights and periods, and levee geometry.