Interior Flooding Analysis – St. Bernard Parish and Lower Ninth Ward, Orleans Parish

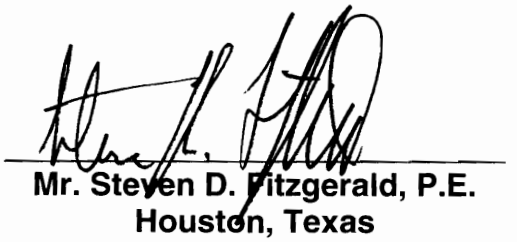
Hurricane Katrina, August 2005

New Orleans Area, Louisiana

Expert Opinion Report

Robinson v. United States

Prepared by



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Houston, Texas
December 18, 2008

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Preface

This expert report has been prepared at the request of the United States, in *Robinson v. United States,* to assess the flooding during Hurricane Katrina in the St. Bernard Basin (polder) made up of the Lower Ninth Ward, Orleans Parish and a portion of St. Bernard Parish in southeast Louisiana.

I, Steven D. Fitzgerald, P.E. (Texas No. 55832), am a civil engineer specializing in hydrology, hydraulics, and flood damage reduction projects. I have 29 years of experience in open channel, riverine, and overland flow applications. I have analyzed, designed, reviewed, and managed numerous watershed studies, and flood damage reduction projects. In November 2005, I had the privilege to join the Corps of Engineers' Interagency Performance Evaluation Task Force as a co-lead of the Interior Drainage team to assess the technical performance of the hurricane protection system in the New Orleans area during Hurricane Katrina. My professional resume is in Appendix A. My hourly rate in this case is $150 per hour. The opinions presented in this report are my own and not those of my current employer, the Harris County Flood Control District, Houston, Texas, or any organizations with which I am affiliated.

I prepared this expert report with support from the Corps of Engineers' New Orleans District office led by Mr. Robert Bass and the Corps of Engineers' Hydrologic Engineering Center led by Mr. Jeff Harris, hereinafter referred to as the interior drainage team. I also consulted with Dr. Joannes Westerink and Dr. Don Resio (sometimes referred to in this report as the hydrodynamics team) and Mr. Bruce Ebersole.

This expert report and the opinions presented rely on the best available technical information and data. If additional information or data becomes available, I reserve the right to revise the conclusions and opinions in this report.

Executive Summary

The objective of this interior flooding analysis report is to calculate the amount of flooding in different parts of the St. Bernard basin when storm surge and/or waves enter the basin during Hurricane Katrina under different scenarios. To accomplish this, we developed a hydraulic model based on the IPET HEC-RAS model, modified with updated and improved hurricane surge and wave input hydrographs from Drs. Westerink and Resio, and with guidance from Mr. Bruce Ebersole on breach trigger elevations. Using this improved HEC-RAS hydraulic model, we ran the following scenarios to determine maximum water surface elevations:

- MRGO and marsh conditions as they existed in 2005 at Hurricane Katrina landfall (U.S. Scenario 1; Plaintiffs' Scenario 1)
- MRGO as designed and pre-MRGO (1956) marsh conditions (U.S. Scenario 6; Plaintiffs' Scenario 3)

The U.S. Scenario 1 results replicated the actual Hurricane Katrina water level observations and timing quite well considering the scale, dynamic nature, and complexity of the Hurricane Katrina event.

The results show that the maximum water surface elevations are virtually identical for both scenarios.

Through some additional model runs and volume calculations, we determined that without the IHNC breaches, the maximum water surface elevations are virtually identical to the actual Katrina scenario. The overtopping and breaches along MRGO had a significant effect on the maximum water surface elevations compared to the IHNC breaches.

1. Introduction

1.1. Hurricane Katrina

Hurricane Katrina struck the New Orleans area early on the morning of August 29, 2005, as a large Category 3 storm (surface winds about 115 mph). Twenty-four hours earlier, the storm had been the largest Category 5 (surface winds 160 mph) and the most intense storm on record within the northern Gulf of Mexico in terms of central barometric pressure. Its intensity, size, and long path through the gulf built up record levels of surge and waves, larger than any previous storm to strike the area or the North American continent. In Louisiana, the east-facing protection levees of Orleans, St. Bernard, and Plaquemines Parishes bore the brunt of Katrina's storm, experiencing surge and waves significantly beyond their design levels. [IPET, Vol. I.] Hurricane Katrina also produced significant rainfall that contributed to the flooding depths. Beginning the afternoon of August 28, the New Orleans area received 8 – 14 inches over the next 24 hours. [IPET, Vol. VI]

1.2 Study Objective

The objective of the interior drainage analysis is to calculate the amount of flooding in various parts of the St. Bernard basin when storm surge and/or waves enter the basin during a Hurricane Katrina. Specific objectives are:

- Develop hydrologic and hydraulic models to replicate the water levels for the Hurricane Katrina event. (U.S. Scenario 1, Plaintiffs' Scenario 1)
- Use these models to calculate water levels if the Mississippi River Gulf Outlet (MRGO) had been at design dimensions and the marsh in and around MRGO had been at 1956 conditions when Hurricane Katrina made landfall. (U.S. Scenario 6, Plaintiffs' Scenario 3)
- Estimate the water volume from each of the sources – rainfall, overtopping, and breaches – for each scenario.

1.3 St. Bernard Basin

The St. Bernard basin shown in Figure 1 is located southeast of downtown New Orleans. It is bounded by the Mississippi River, Inner Harbor Navigation Canal (IHNC), Gulf Intracoastal Waterway (GIWW), Mississippi River Gulf Outlet (MRGO), and coastal marsh to the south. Total surface area is about 77 square miles, of which about 46 square miles is low, coastal marsh between MRGO and the 40 Arpent levee. The developed area between the Mississippi River and the 40 Arpent levee is about 31 square miles. The Lower Ninth Ward, which is in Orleans Parish and the City of New Orleans, is adjacent to the IHNC. East of the Lower Ninth are the communities of Arabi and Chalmette. Moving southward through Meraux, Violet, Caernarvon, and Verret, development becomes more sparse.

There are two federal levee systems that define the St. Bernard basin. The Mississippi River Flood Protection System along the river is designed for river flood flows. The other one is a portion of the Lake Pontchartrain and Vicinity Hurricane Protection Plan designed for hurricane surge and waves. The two segments in the St. Bernard basin are the Chalmette and Chalmette Extension levees. In addition to the levee and floodwalls, there are 6 road closure structures, 2 water control structures, and 1 gravity drainage structure. The St. Mary's pump station located in the Chalmette Extension levee, near

the end of the 40 Arpent levee, is not part of the federal project. The 40 Arpent levee is part of the local flood protection system, not the federal hurricane protection system.

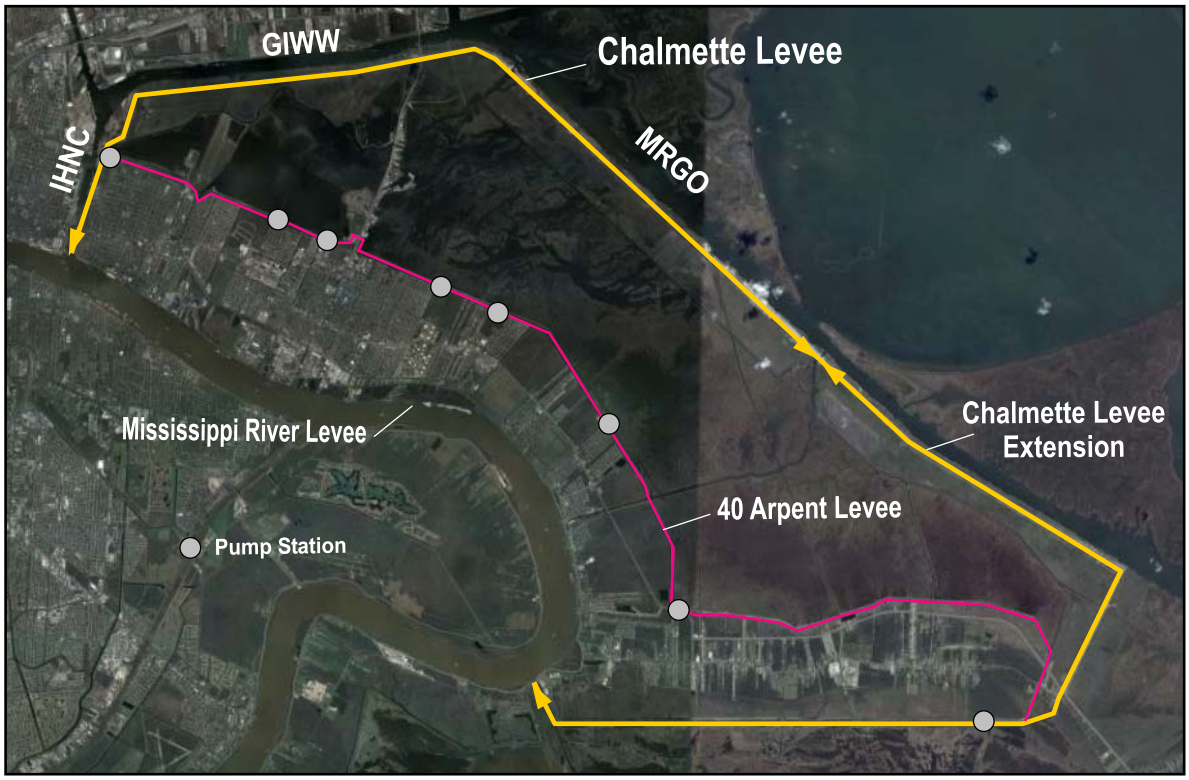


Figure 1. St. Bernard Basin and Features *(aerial Google Earth)*

1.4. Previous Studies

Several studies were performed after Hurricane Katrina to assess the performance of the hurricane protection system in the New Orleans area. The studies are listed below with a brief description of their interior drainage work.

- *"Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System," Final Report of the Interagency Performance Evaluation Task Force (IPET), U.S. Army Corps of Engineers, March 26, 2007*

  A task force was assembled by the Corps of Engineers to determine the scientific and engineering facts. The task force consisted of experts from the Corps of Engineers, universities, private sector, and other government agencies. The task force obtained as much technical data as possible in the time frame given to perform the analysis and assessments of six basins. Volume VI of the IPET report contains a comprehensive interior drainage section that estimates water levels and volumes for the Katrina event and three what-if scenarios. The IPET Volume VI report, appendices, and associated data and models were used extensively for this report.

- *"The Failure of the New Orleans Levee System during Hurricane Katrina," Team Louisiana, Louisiana Department of Transportation (Team Louisiana), State Project No. 04-92-0022, December 18, 2006*

  A team was commissioned by the Louisiana Department of Transportation and Development to collect forensic data related to the failure of the levee systems around greater New Orleans. The team consisting of Louisiana-based academic and private sector experts collected data water levels and time data to help develop flood timelines for the basins. Some of the Team Louisiana timeline results for the St. Bernard basin were compared to the results of this report.

- *"Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005," Independent Levee Investigation Team (ILIT), Volume 1, July 31, 2006.*

  A team lead by the University of California at Berkeley consisted of experts from universities, the private sector, and federal government. Their investigation focused on three questions - What happened? Why? And what changes are necessary to prevent recurrence of a disaster of this scale? The ILIT report did not contain interior drainage data or information useful for this report.

The studies listed below are the *Robinson vs. United States* Plaintiffs' expert reports related to interior drainage.

- *"Polder Flood Simulations for Greater New Orleans, the neutral MRGO scenario," Kok, M.; Aalberts, M.; Kanning, W.; Maaskant, B.; de Wit, L; Delft University of Technology and Svasek Hydraulics; July 9, 2008*

- *"Polder Simulations for Greater New Orleans, Hurricane Katrina August 2005," Kok, M.; Aalberts, M.; Maaskant, B.; de Wit, L; Delft University of Technology and Svasek Hydraulics; July 30, 2007*

The study below is an expert report prepared by the defendants in *Katrina Canal Breaches Consolidated Litigation*, Civil Action 05-4182 and consolidated cases: Pertaining to Barge, United States District Court, Eastern District of Louisiana, Division K.

- *"Analysis of Flooding of the Lower Ninth Ward and St. Bernard Parish, Hurricane Katrina August 2005, New Orleans, Louisiana" CivilTech Engineering, Inc., June 27, 2008*

  The CivilTech report identifies the timeline of the flooding and sources of floodwaters in the Lower Ninth Ward and St. Bernard Parish. In addition to using information from the IPET and Team Louisiana reports, they collected additional eyewitness information and performed flood simulations using the Sobek-1D2D computer model to develop a realistic flood timeline. I compared the CivilTech timeline and water surface elevations to the results of this report.

2. Model Development

2.1. Models Selected and General Approach

The Hydrologic Engineering Center - River Analysis System (HEC-RAS) unsteady model was used to compute the water surface elevations in the St. Bernard basin. Developed by the USACE, the HEC-RAS unsteady model performs one-dimensional hydraulic calculations for a network of channels as well as weirs and closed conduits. HEC-RAS is used extensively in the United States for watershed studies, mitigation and flood damage reduction projects, and FEMA flood insurance studies. The companion program, Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS), was used to convert the rainfall into runoff, or flow hydrographs, from the land. It, too, is commonly used in the United States.

The general modeling approach is

- Divide the St. Bernard basin into subbasins based on hydraulic and land features. Use the same subbasins for HEC-HMS and HEC-RAS.
- Compute the runoff hydrograph from the rainfall for each subbasin using HEC-HMS.
- Establish the levee and floodwalls crest profile and approximate final breach geometries in HEC-RAS.
- Estimate the wave-only flow over the levee and floodwalls prior to breaching and add to the rainfall-runoff hydrograph. Dr. Resio provided data for this step.
- Using HEC-RAS, estimate the flow over the levees and floodwalls and through the breaches using the surge hydrographs provided by the hydrodynamics team.
- Using HEC-RAS, compute the water surface elevations and stage hydrographs for each subbasin.

The hydraulic simulations begin on August 28, 2005 12:00 CDT and continue until August 30, 2008 24:00 CDT. The starting time represents when the rain began and surge levels were above 2 feet along the MRGO. The ending time is past the peak long enough to depict the recession limb of the interior hydrographs.

2.2. Input Data

The primary source of data for this report is the IPET work and reports. The IPET work effort consisted of several technical and engineering experts across different disciplines collecting and analyzing data simultaneously in order to complete the report within the time allotted. The IPET interior drainage team used the best data available at the time it was needed.

For this report, we were able to reassess the IPET input data and make some improvements to the St. Bernard basin HEC-RAS model. In addition, updated and improved hurricane surge and wave input hydrographs were developed and provided by the hydrodynamics team. [Westerink, 12-2008; Resio, 12-2008]

The IPET Volume VI main report and Volume VI, Appendix 4 contain a complete description of the input data and model parameters. This report will not go into the same level of detail since it is already documented. This report summarizes the input data and includes changes made from what is reported in the IPET reports.

In conjunction with Mr. Bruce Ebersole, I reviewed the input data and information. Even though there are uncertainties and some unknowns, the data is the best available, of typical quality for hydrologic and hydraulic analysis, and is sufficient to meet the objectives of this report.

2.3. Assumptions

As is common when performing hydrologic and hydraulic modeling, assumptions are made to facilitate the analysis. Below are the assumptions made for this analysis:

- Sources known to contribute relatively small volumes of water within the St. Bernard basin were not modeled. This includes water blown over the top of the levees and floodwalls, backflow through the pumps, and groundwater.
- Only primary internal drainage canals and closed conduits are modeled. Small canals, collector ditches, and storm sewers less than 21 inches in diameter are not modeled. They have very little effect on flood levels after they become inundated early in the storm.
- Flow in canals and closed conduits were not reduced by debris blockages. This most likely affected the outflow more than the inflow in some subbasins.
- Since the St. Bernard basin pump stations did not operate during the storm, no pump flow is included in the model. Some stations operated for a limited time up through part of August 28 and after the storm to remove storm water from the basin.

2.4. Hydrologic Analysis (HEC-HMS)

The results from the IPET HEC-HMS model was used for this analysis. A brief description of the rainfall and method used is presented below. For a complete description, see IPET Vol. VI, Appendix 4.

HEC-HMS version 3.01 was used in the IPET analysis. Subbasin boundaries in the HEC-HMS model correspond to storage areas defined in the HEC-RAS model (see Hydraulic Model section below for description of delineation of subbasin boundaries). Rainfall for each subbasin was determined using radar-rainfall estimates from the National Weather Service. The Soil Conservation Service (SCS) curve number and the SCS dimensionless unit hydrograph methods were used to compute runoff hydrographs given basin average precipitation. Land use and soil data were used to estimate SCS curve numbers and lag times.

The St. Bernard basin received 9 – 12 inches of rainfall over 24 hours which is a 4 – 10% probability (25 – 10 year frequency) event for southeast Louisiana. Figure 2 shows the total storm rainfall over the basin and Figure 3 shows a rainfall hyetograph and runoff hydrograph for one of the subbasins.

The runoff volume computed by HEC-HMS for each of the subbasins is in the range of 7 – 10 inches. Rainfall losses of about 2 inches is reasonable. Total volume contributed by rainfall was estimated to be 34,320 acre-feet (8.4” average over entire basin).

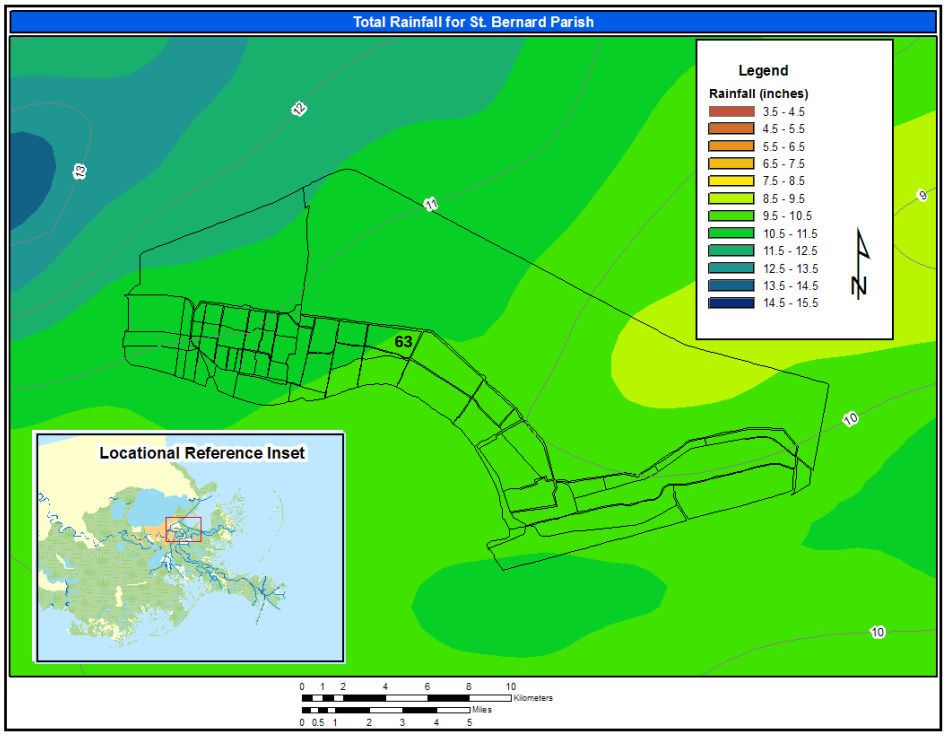


Figure 2. Total Storm Rainfall (inches) *(IPET VI-4-14, Figure 4-5)*

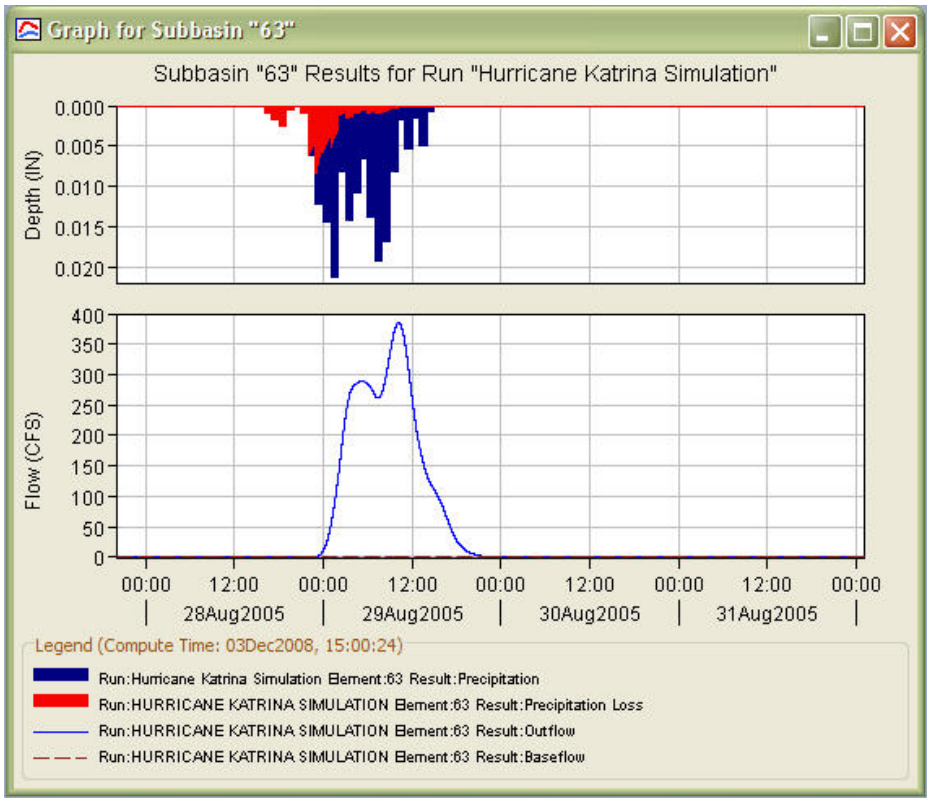


Figure 3. Rainfall and Runoff Hydrograph Example from HEC-HMS; Subbasin 63 *(IPET HEC-HMS St. Bernard model)*

2.5. Hydraulic Analysis (HEC-RAS)

The same custom version of HEC-RAS developed for the IPET analysis was used for this analysis, Version 3.2 Beta. Some changes were made in the IPET HEC-RAS for this analysis. A brief description of each component of the model is presented in this section with changes noted. For a complete description of the IPET HEC-RAS model development, see IPET Vol. VI, Appendix 4.

2.5.1. Terrain and Datum

The terrain, or ground topography, used is based on 2004 LIDAR data collected for the Federal Emergency Management Agency. The datum of the LIDAR is NAVD88 (1994, 1996 epoch) and the vertical accuracy is +/- 0.7 ft. The horizontal projection is Louisiana State Plane South 1983 feet. Figure 4 is a representation of the St. Bernard basin terrain.

After the IPET HEC-RAS model was developed and tested by the IPET interior drainage team, the adjustment between the 1994, 1996 epoch and the datum/adjustment adopted for the IPET study, NAVD88 (2004.65) was determined to be from -0.2 to -0.7 ft in the New Orleans area. In light of the accuracy of the terrain data and other input data such as the observed high water marks, no adjustment was necessary because (1) the terrain data accuracy was +/- 0.7 ft, which was within the -0.7 ft adjustment; (2) the differences were too slight to warrant the work that would be involved in recalculating everything; and (3) results of modeling have an error bar equal to or greater than 0.7.

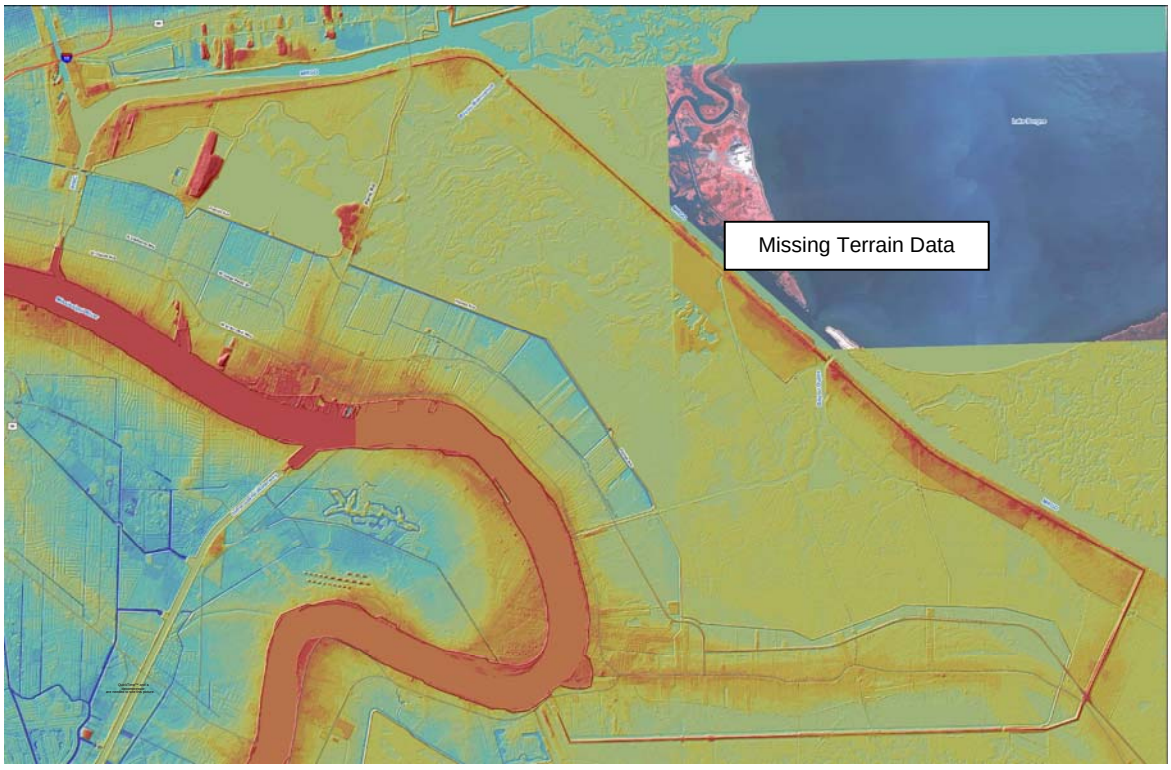


Figure 4. St. Bernard Basin Terrain *(CivilTech Report, Exhibit 5)*

2.5.2. Subbasins

Figure 5 shows the 67 subbasins delineated within the St. Bernard basin using geographical features such as drainage canals, levees, railroads, roads, elevated areas, and natural high ground. Subbasins are referred to as storage areas in HEC-RAS because stage-volume relationships are developed using the LiDAR data. Storage areas are hydraulically connected to the canals by using lateral weirs. Storage areas are interconnected to each other with a weir, culverts, and/or a linear routing method. Flow can go in either direction, and submergence on a weir is accounted for. Both the weir coefficients and the linear routing coefficients are used as calibration parameters to slow down or increase the spread of the water through the system.

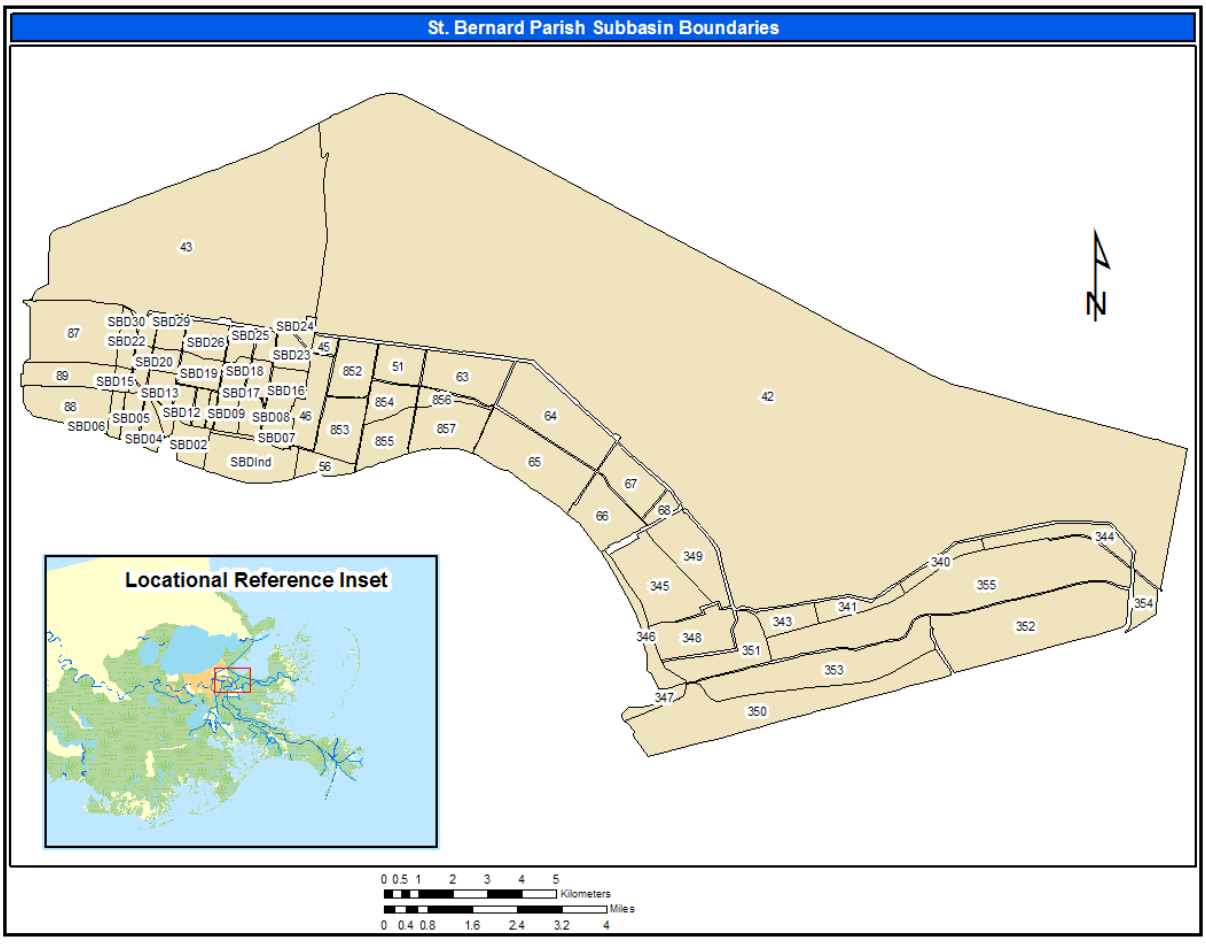


Figure 5. St. Bernard Subbasin Boundaries *(IPET VI-4-5, Figure 4-1)*

2.5.3. Levees and Floodwalls

The IPET HEC-RAS Chalmette and Chalmette Extension levee and floodwall crest elevations were carefully reviewed for this report using the pre-Katrina 2001 LiDAR data, post-Katrina 2005 LiDAR data, and post-Katrina field surveys. Modifications to the crest elevations were made as necessary in collaboration with Bruce Ebersole.

Using as accurate as possible levee and floodwall crest elevations is important for this analysis because

- crest elevations have a significant affect on the inflow into the basin,
- wave setup and wave overtopping are included in the calculation of the inflows, and
- small differences in surge elevations are anticipated for the various scenarios.

The levee reach designations are shown on Figure 6.

Some changes were made to the crest elevations along the non-federal 40 Arpent levee from what was in the IPET HEC-RAS model to more closely match the LiDAR data.

2.5.4 Breaches

During the storm, two breaches developed along the IHNC floodwall and a series of long breaches developed along the levee, floodwalls, and two water control structures adjacent to the MRGO. No significant breaching occurred along the southern most part of the Chalmette Extension levee or the levee adjacent to the GIWW. Figure 6 shows the approximate location of the breaches.

In the HEC-RAS model, the final physical geometry of a breach is approximated by a width and final sill elevation. The irregular breaches along MRGO were aggregated into 11 breaches for modeling purposes. Determining when the breach commenced and reached its final geometry during the inflow is difficult. Mr. Bruce Ebersole provided guidance for determining when the breach occurred, which is referred to as the trigger elevation. [Ebersole, 12-2008] The duration was estimated based on eyewitness accounts, other observational data, and professional judgment. In the HEC-RAS model breach routine, the crest elevation downgrades to the final elevation uniformly with each time step for the duration given. Table 1 shows the breach parameters.

Table 1. Breach Data

Approx. Centerline Station	Bottom Width (ft)	Bottom Elevation (ft)	Water Surface Trigger Elev. (ft)	Formation Time (hour)
IHNC Reach				
South	825	3	12.3	0.33 (20 min)
North	235	1	9.0	0.33 (20 min)
MRGO Reach				
40265	8600	10	13.0	1.5
47430	1800	7	14.5	1.5
50830	1600	9	14.7	1.5
53750	2000	10	15.0	1.5
56820	1400	10	14.5	1.5
60380	400	5	14.5	1.5
62800	400	8	14.0	1.5
66800	400	5	14.5	1.5
70790	2100	10	14.5	1.5
76385	3800	10	16.0	1.5
82475	500	8	16.0	1.5

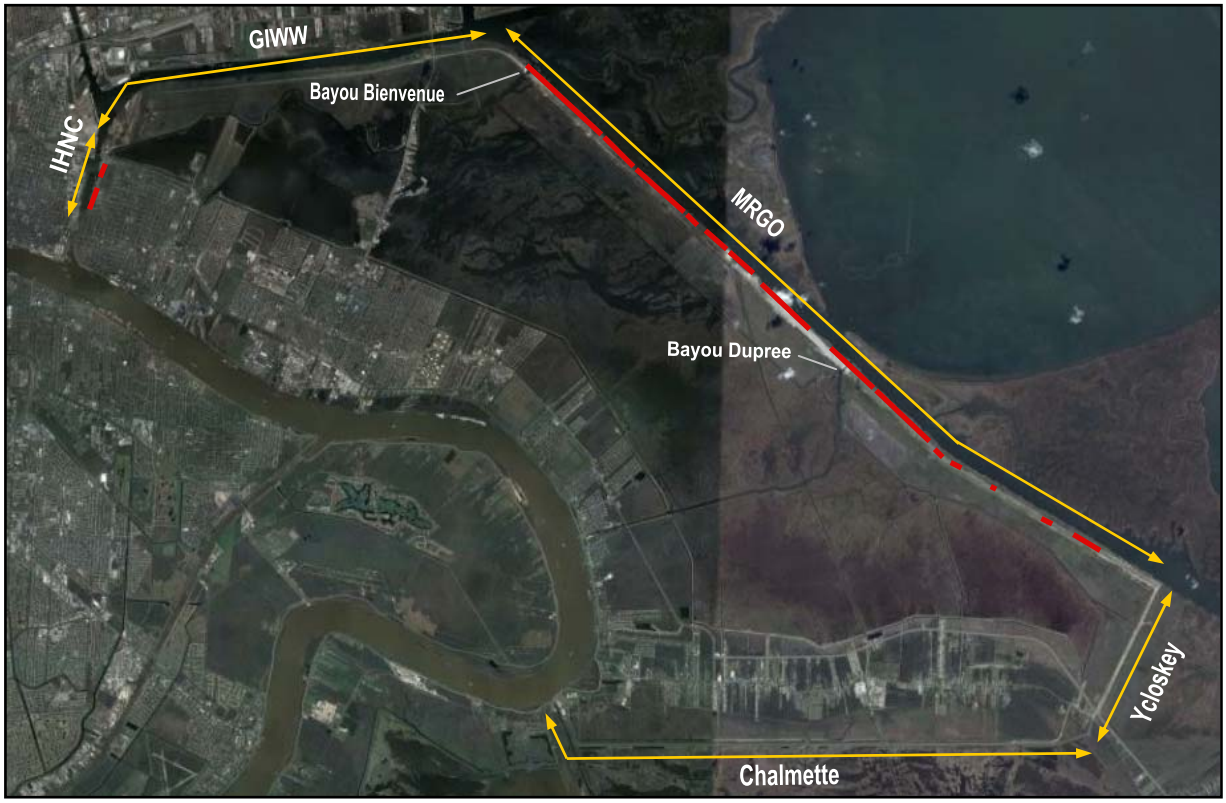


Figure 6. HEC-RAS Levee Reach Designations (shown in yellow) and Approximate Breach Locations (shown in red) *(aerial Google Earth)*

2.5.5. Surge and Wave Inflow

Besides rainfall, the other inflow into the St. Bernard basin is levee and floodwall overflow and breaching. Overflow was extensive along the levee and floodwalls adjacent to the IHNC and MRGO. Some overflow occurred along the GIWW and southern most levee segment.

The total overflow is made up of the freeflow component and wave overtopping component. The wave overtopping component occurs first before the surge elevation reaches the crest elevation. The freeflow component occurs once the surge elevation reaches the crest, and includes contributions from both the surge and wave overtopping.

Surge hydrographs were provided by the hydrodynamics team for several locations adjacent to the Chalmette and Chalmette Extension levee and floodwalls. [Westerink, 12-2008] The interior drainage team scaled the surge hydrographs to more closely match the observed data. The scale factors varying from 1.04 to 1.12 were provided by Bruce Ebersole. Computed surge hydrographs were selected for input into HEC-RAS at the ends of each of the levee reaches shown in Figure 6, except for the IHNC. The stage measured at the IHNC lock staff gage was used in the IHNC reach. [IPET V-70]

The surge hydrographs along the levee and floodwalls adjacent to MRGO included wave setup for the actual Katrina scenario (U.S. Scenario 1, see Table 2) as provided by the hydrodynamics team. [Resio, 12-2008] The maximum wave set up is 0.6 feet at the locations of the surge hydrographs used for the interior drainage analysis.

Wave overtopping was estimated by the hydrodynamics team [Resio, 12-2008] at 21 points along MRGO. An average wave overtopping flow hydrograph was developed by the interior drainage team and added to the Storage Area 42 rainfall hydrograph.

3. Flood Simulations Analyzed

Interior drainage analysis was performed for the two flood simulations shown in Table 2 below.

Table 2. Flood Simulations

United States Scenario	Plaintiffs' Scenario	MRGO Reach 1	MRGO Reach 2	Chalmette Levee	Marsh	Description
1 "Katrina Real Run"	1	2005 pre-Katrina dimensions	2005 pre-Katrina dimensions	2005 pre-Katrina dimensions	2005 pre-Katrina conditions	Conditions at Hurricane Katrina landfall.
6 "MRGO as Designed" (1956 wetlands)	3	Ideal MRGO (approximate design dimensions)	Ideal MRGO (approximate design dimensions)	2005 Pre-Katrina dimensions	1956 Pre-MRGO conditions	Conditions at Katrina landfall, if MRGO had been at design dimensions and marsh had been in 1956 pre-MRGO condition.

4. Flood Simulation – U.S Scenario 1: Katrina Real Run (Plaintiffs' Scenario 1)

The purpose of modeling the actual Katrina scenario is to develop an interior drainage model to represent the hydraulic conditions as accurately as possible and replicate the water levels within a reasonable accuracy.

4.1. Calibration

Because the physical features were represented realistically and the surge and wave input used actual physical features, the need for calibration of the HEC-RAS model to more closely match maximum water surface levels with observed high water marks in the subbasins was minimal.

- The IHNC south breach bottom elevation was increased from 1 foot to 3 feet to more closely match the water surface elevations and timing during the initial part of the water rise in the Lower Ninth Ward.
- The formation time of the breaches along the levee adjacent to MRGO was increased from 1.0 hour to 1.5 hours.
- The weir coefficient along the 40 Arpent Canal was adjusted to match the observed filling of the subbasins.

Table 3 below shows the computed maximum water surface elevations at the locations shown in Figure 7. The HEC-RAS model results match well with the observed high water marks.

Table 3. Katrina Real Run, Maximum Water Surface Elevation *(in feet, NAVD88 (2004.65)*

Location (See Figure 7)	**U.S. Scenario 1, Katrina Real Run**	**Observed HWM***
#1	10.9	--
#2 and A	10.9	10.5
# 3	11.1	10.0
#4	11.1	11.9
#5	11.3	11.0
#6	11.2	11.0
(B)	11.1	11.9
(C)	11.3	11.0
#7	11.3	10.5
#8	11.3	10.0
#9	11.3	10.8
#10	11.3	10.8

* Observed high water marks are from the IPET report and represent the higher elevations within the subbasin.



Figure 7. Stage Hydrograph Locations (X – Plaintiffs' locations, ◇ - similar locations to 2008 Kok report) *(aerial Google Earth)*

4.2. Results

Water depth maps over time are shown in Figures 8a-j. The maximum water depth reached in each of the subbasins is shown in Figure 8k. Note that these represent the water depth rising within each HEC-RAS subbasin or storage area from rainfall, flow over levees and floodwalls, and flow through breaches. It is not a representation of water flowing across a subbasin.

For the Lower Ninth Ward at Location #1, the model matches closely with the eyewitness accounts and rising water level data. Filling begins 3:50 am when the north breach near Florida Avenue occurs. The south breach near N. Clairborne Avenue occurs between 7:00 and 7:30 am. The modeled maximum water levels match closely with the observed high water marks in the Lower Ninth Ward. [IPET IV-197, Figure 136]

East of Paris Road, Location #5 and C, the model matches closely with rising water level data and videos taken during the storm. Houses in this area were reported to have flooded 8 to 10 feet deep by about 9:30 am. The model shows depths reaching 8 feet around 10 am and reaching a peak of 11.3 feet compared to the observed estimate of 10.8 feet. [IPET IV-199 and Figure 1356]

Along the levee adjacent to MRGO, the model indicates wave overtopping began around 3 am on August 29. Surge overtopping is estimated to have begun at the flood wall under Paris Road around 5 am. By 6:30 am, surge overtopping had begun along most

of the entire reach of MRGO. The model calculated that the first flow through a breach occurred about 6 am, and by about 7 am flow, occurred through all the breach locations adjacent to MRGO. Formation time for each breach was assumed to be 1.5 hours.

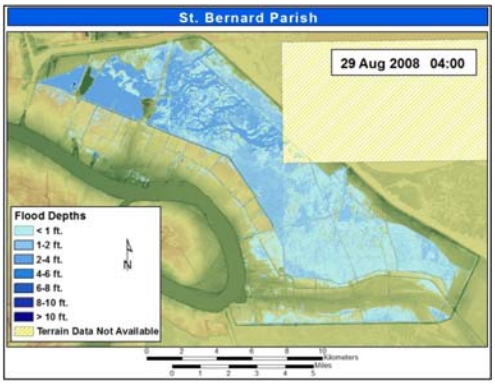


Figure 8a

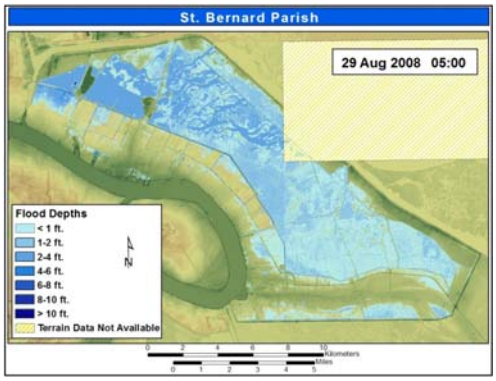


Figure 8b

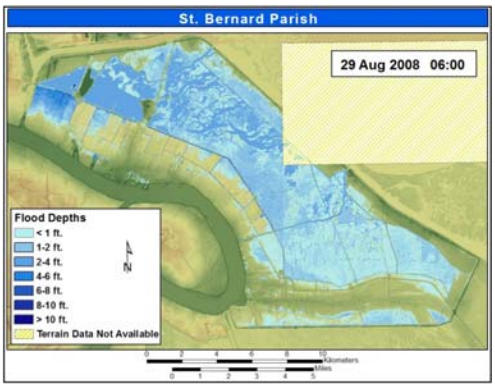


Figure 8c

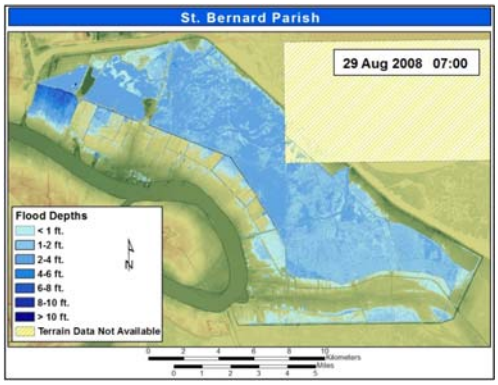


Figure 8d

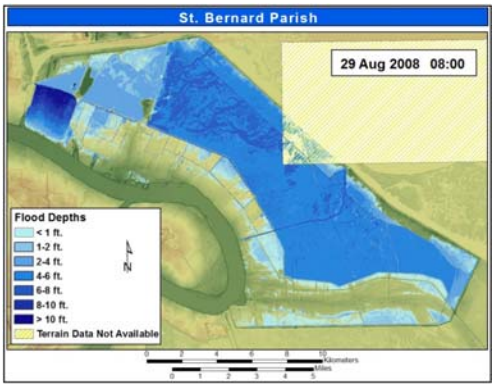


Figure 8e

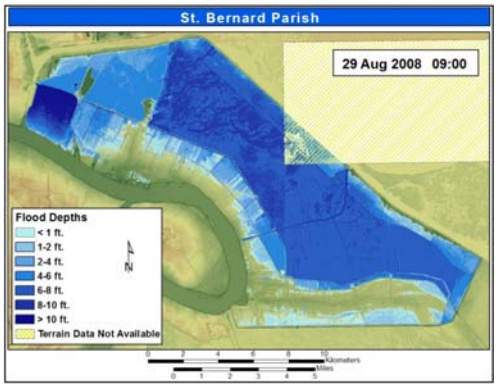


Figure 8f

Figures 8a-f. U.S. Scenario 1, Katrina Real Run - Water Depth Time Series

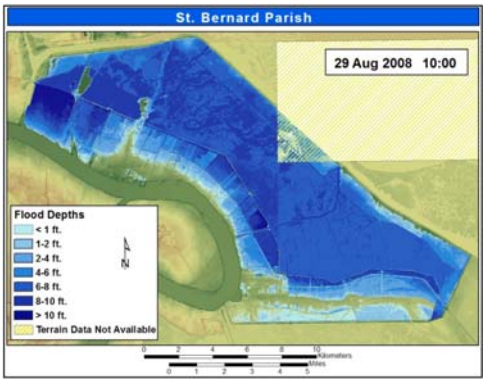


Figure 8g

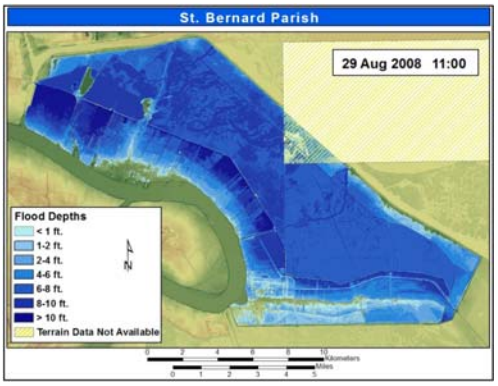


Figure 8h

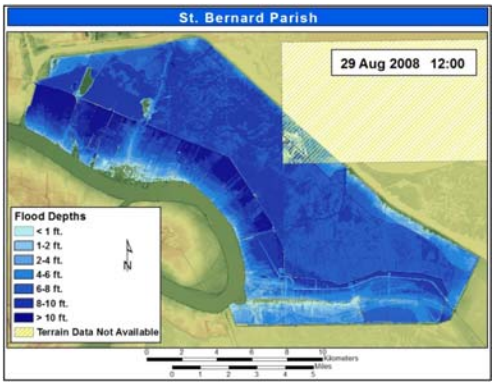


Figure 8i

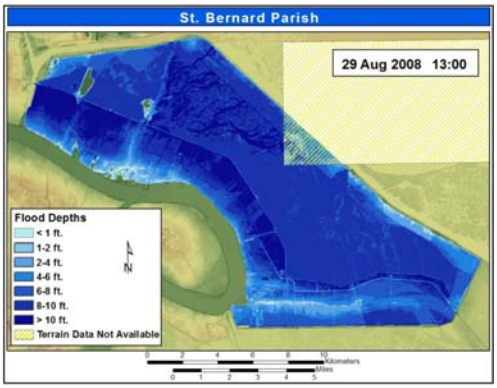


Figure 8j

Figures 8g-j. U.S. Scenario 1, Katrina Real Run - Water Depth Time Series

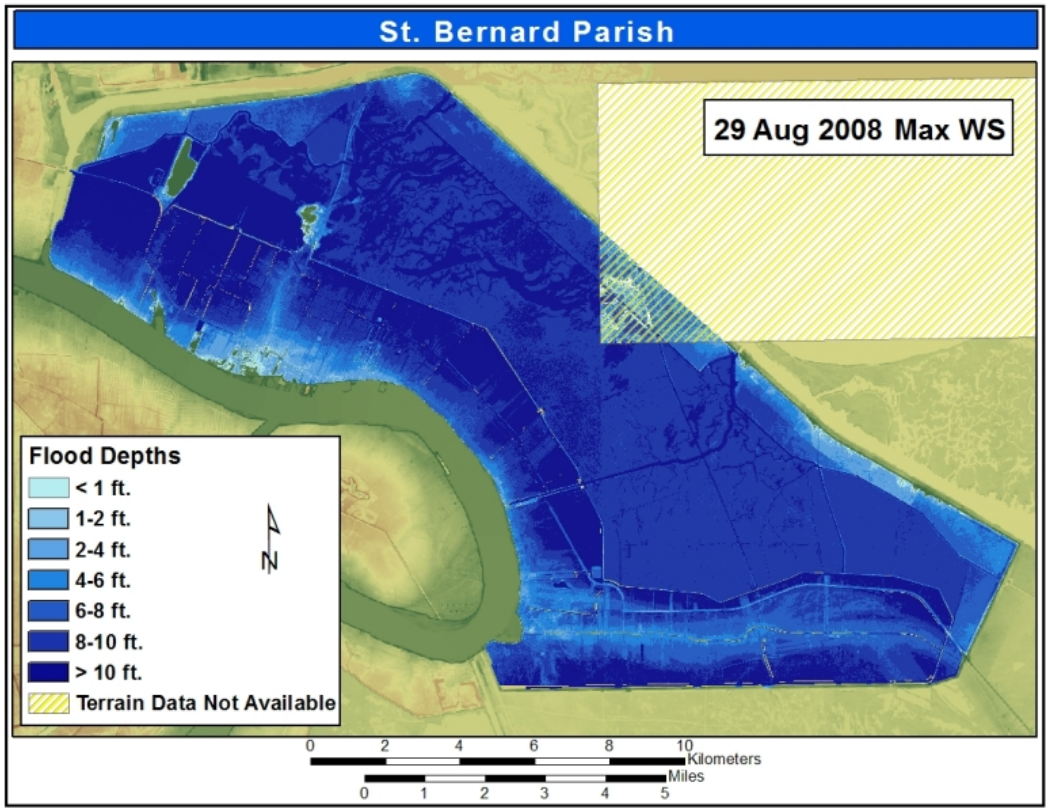


Figure 8k. U.S. Scenario 1, Katrina Real Run – Maximum Water Depth

Subbasin stage hydrographs at several locations (Figure 7) are shown in Figures 9a-f.

The computed water volumes were approximated and are provided below to indicate the general magnitude of water from each source.

Source	Volume (acre-feet)	Percent
Rainfall	34,320	8%
Wave Overtopping	17,250	4%
Surge Overtopping	23,920	6%
Breaches	344,690	82%
Total	420,180	100%

About 70% of the breach volume flowed through the breaches adjacent to MRGO between Bayou Dupree and Bayou Bienvenue (see Figure 6). About 14% of the volume flowed through Bayou Dupree and the breaches to the south. About 12% came through the IHNC breaches.

It is my professional opinion that the U.S. Scenario 1 HEC-RAS model replicated the actual Katrina event in the St. Bernard Basin quite well. The differences between model results and observed data are within reasonable limits, especially considering the scale, dynamic nature, and complexity of the Hurricane Katrina event.

In order to isolate the effect of the water from the IHNC breaches on the maximum water surface elevation, the U. S. Scenario 1 model was run for two cases – (1) without the IHNC south breach, and (2) without the north and south IHNC breaches. Results are shown in Table 4.

Table 4. U.S. Scenario 1 Comparison of Maximum Water Surface Elevation With and Without IHNC Breaches

Location (See Figure 7)	**U.S. Scenario 1**	**U.S. Scenario 1, Without IHNC South Breach**	**U.S. Scenario 1, Without South and North IHNC Breaches**
#1	10.9	10.9	10.9
#2	10.9	10.9	10.9
# 3	11.1	11.0	10.9
#4	11.1	11.0	10.9
#5	11.3	11.1	10.9
#6	11.2	11.0	10.9
#7	11.3	11.1	10.9
#8	11.3	11.1	10.9
#9	11.3	11.0	10.9
#10	11.3	11.0	10.9

While the IHNC breaches caused a rapid rise in water levels in the Lower Ninth Ward, the maximum water surface elevation was primarily influenced by the water from the breaches along the MRGO. On the U.S. Scenario 1 stage hydrograph at Location #1 (Figure 9a) in the Lower Ninth Ward, one can see when the rainfall, IHNC north breach, IHNC south breach, and the overtopping and breaching along MRGO began contributing to the water level in that area. Even without the IHNC breaches, the maximum water surface elevation in the Lower Ninth Ward area would have been nearly identical.

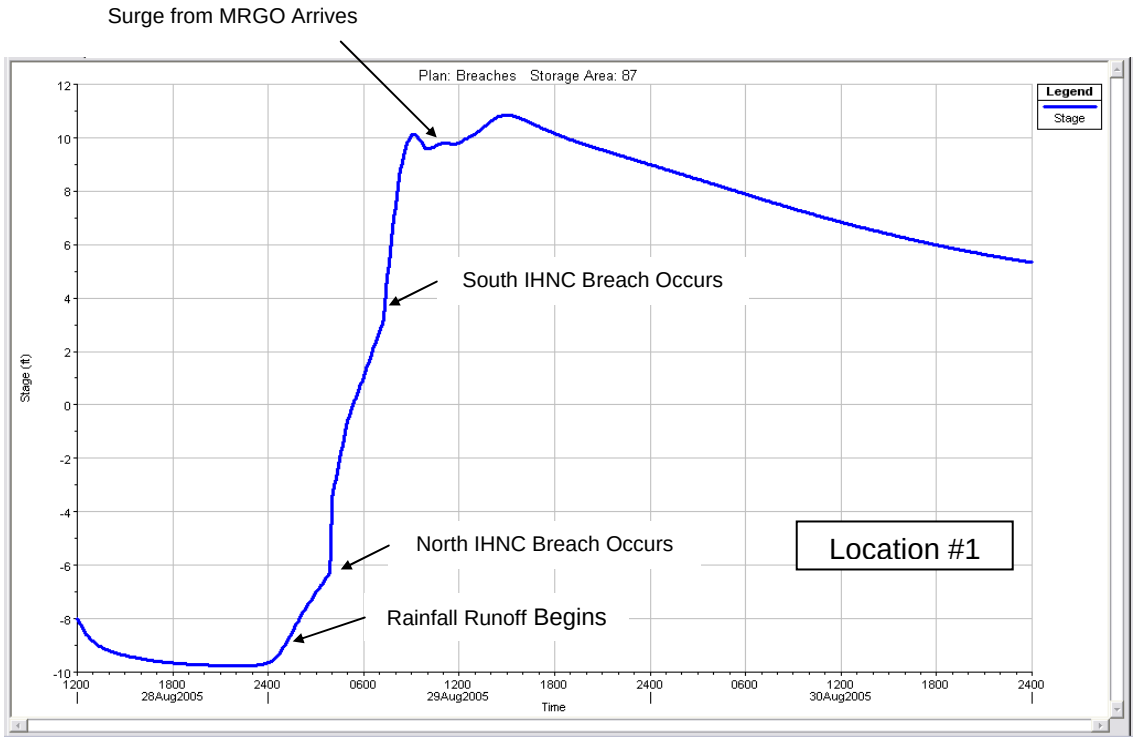


Figure 9a. U.S. Scenario 1, Katrina Real Run – Location #1 Stage Hydrograph

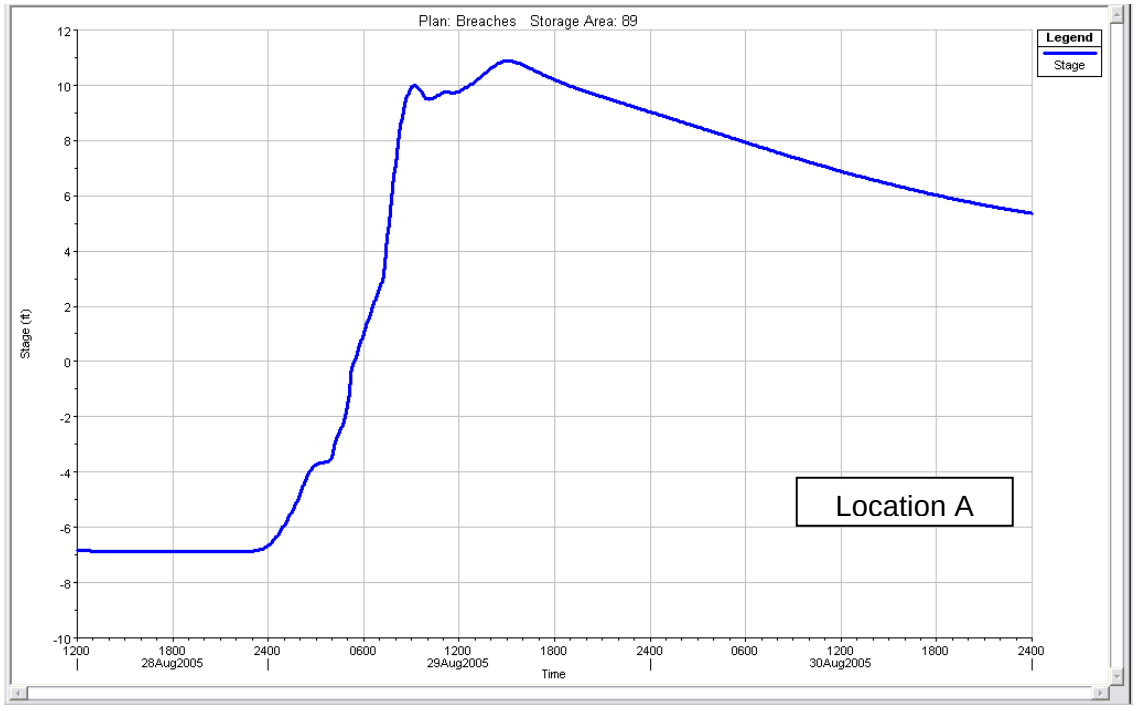


Figure 9b. U.S. Scenario 1, Katrina Real Run – Location A Stage Hydrograph

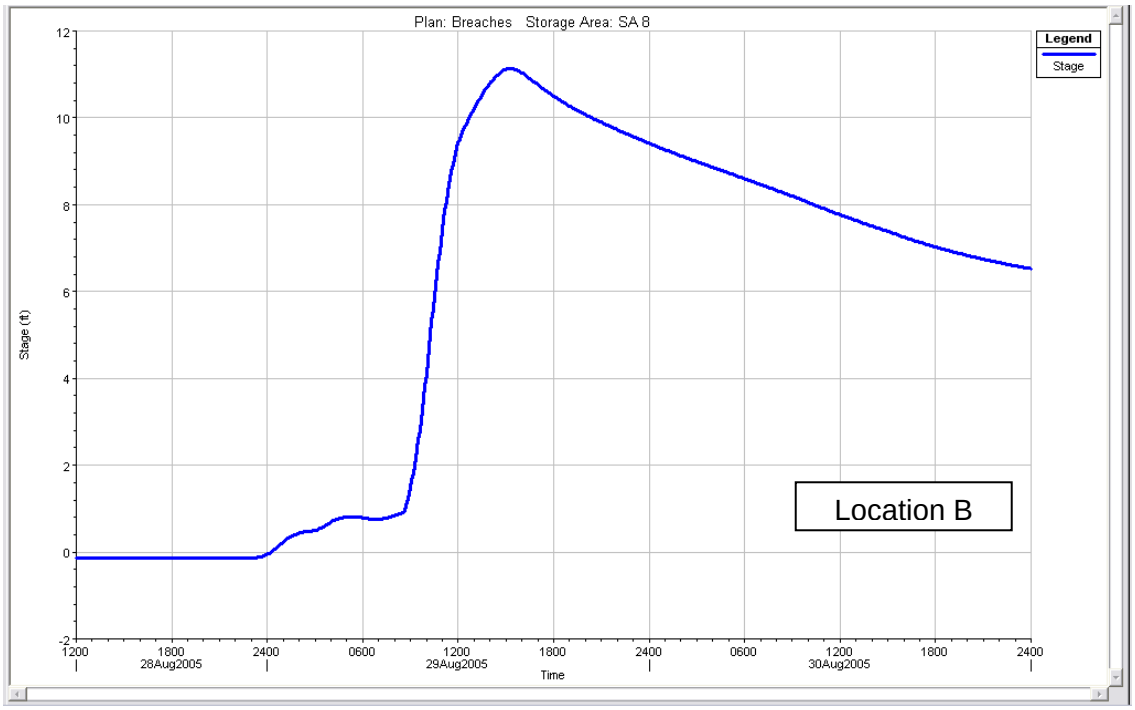


Figure 9c. U.S. Scenario 1, Katrina Real Run – Location B Stage Hydrograph

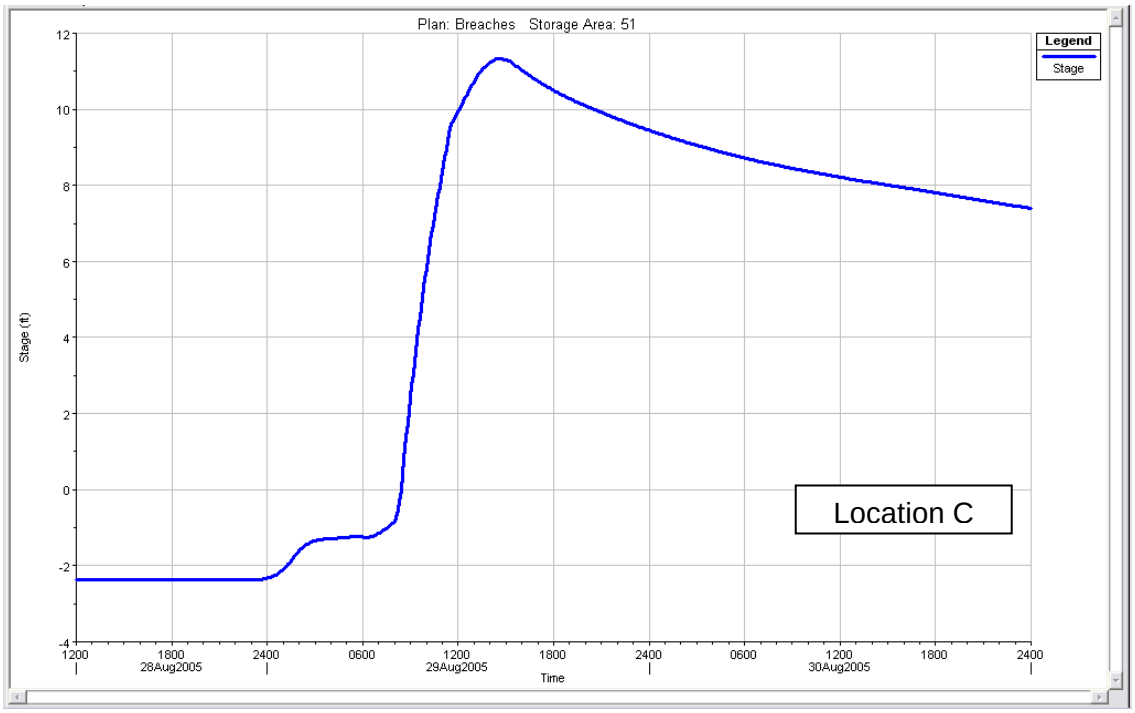


Figure 9d. U.S. Scenario 1, Katrina Real Run – Location C Stage Hydrograph

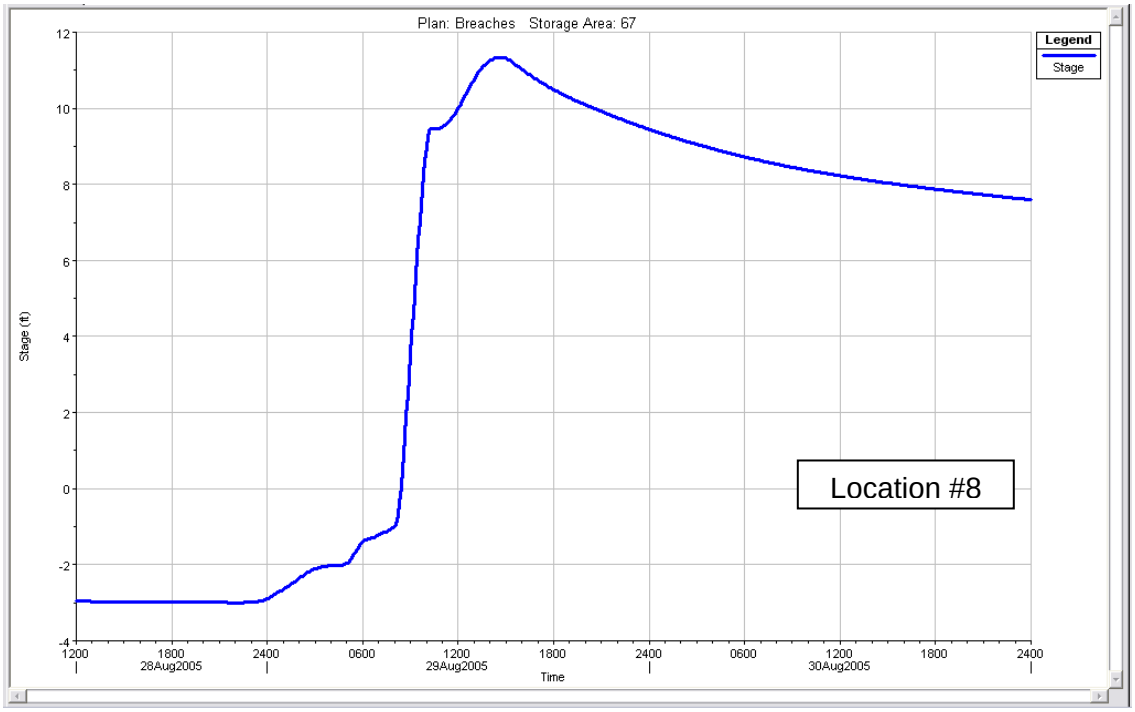


Figure 9e. U.S. Scenario 1, Katrina Real Run – Location #8 Stage Hydrograph

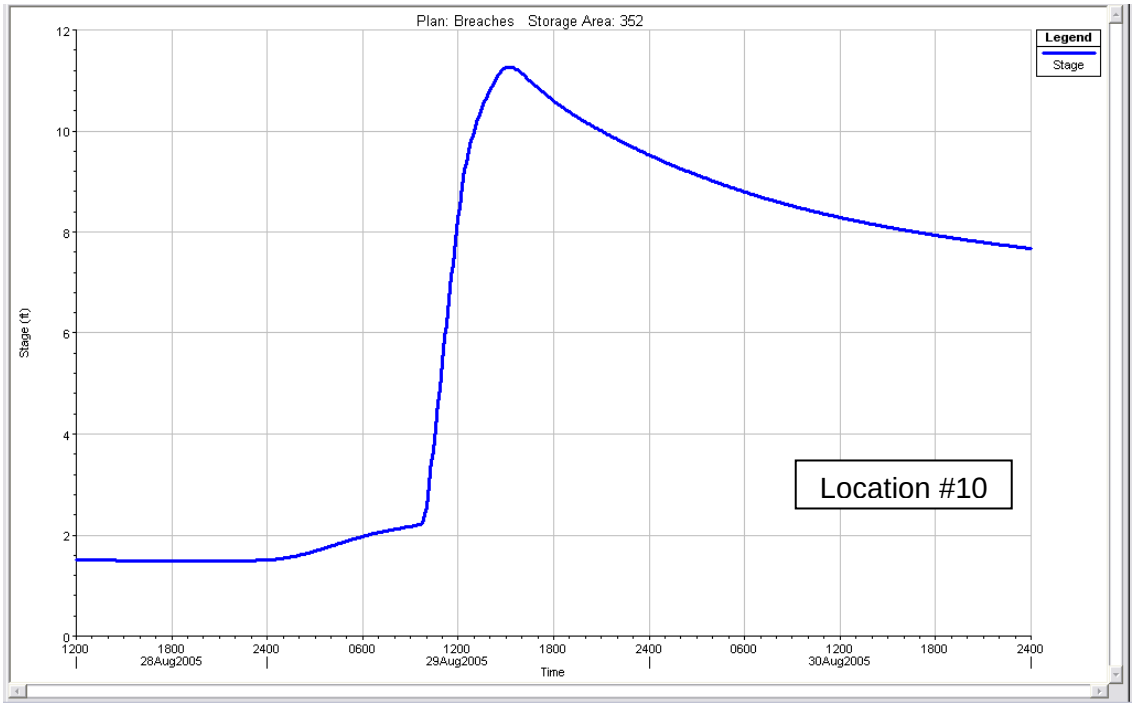


Figure 9f. U.S. Scenario 1, Katrina Real Run – Location #10 Stage Hydrograph

5. Flood Simulation - U.S. Scenario 6: MRGO as Designed, 1956 Wetlands (Plaintiffs' Scenario 3)

The U.S Scenario 1 HEC-RAS model was used to model U.S Scenario 6. These scenarios are the same except MRGO was assumed to be in the as designed condition and the wetland and marsh topography was pre-MRGO, or 1956 conditions.

The hydrodynamics team provided the surge stage hydrographs and wave overtopping data for Scenario 6. [Westerink, 12-2008; Resio 12-2008] Since the surge and wave data for Scenario 6 are very similar to the data for Scenario 1, the maximum water levels in the St. Bernard basin nearly identical. A comparison of the U.S. Scenario 1 and 6 maximum water surface elevations is shown in Table 5 below.

Table 5. U.S. Scenario 1 and 6, Maximum Water Surface Elevation Comparison *(in feet, NAVD88 (2004.65)*

Location (See Figure 7)	**U.S. Scenario 1, Katrina Real Run**	**U.S. Scenario 6, MRGO as Designed, 1956 Wetlands**	**Difference (1 minus 6)**
#1	10.9	10.7	0.2
#2 and A	10.9	10.6	0.3
# 3	11.1	11.1	0.0
#4	11.1	11.1	0.0
#5	11.3	11.3	0.0
#6	11.2	11.2	0.0
(B)	11.1	11.1	0.0
(C)	11.3	11.3	0.0
#7	11.3	11.3	0.0
#8	11.3	11.4	-0.1
#9	11.3	11.3	0.0
#10	11.3	11.3	0.0

We assumed the breaches in U.S. Scenario 6 developed in the same manner as in U.S. Scenario 1 because the surge hydrographs and wave overtopping were similar.

6. Comparison to Plaintiffs' Results

The Plaintiffs' expert interior drainage reports [Kok, 2007; Kok 2008] did not include model results for U.S. Scenario 6 (Plaintiffs' Scenario 3); therefore, a comparison will only be made between the U.S. Scenario 1 with Plaintiffs' Scenario 1, the actual Katrina event.

The Plaintiffs' interior drainage experts used the Sobek-1D2D software package and some of the source data from the IPET work. There are some differences in modeling approach and inputs, such as the timing of the breaches along the IHNC. However, it most likely doesn't impact the maximum water surface in the Lower Ninth Ward due to the volume of water entering from the levee breaches along MRGO.

A comparison of the maximum water surface elevations at approximately the same locations is shown in Table 6. Generally, our model more closely matched the observations.

Table 6. Comparison of Maximum Water Surface Elevation, U.S. Scenario 1 and Plaintiffs' Scenario 1, Katrina Real Run *(in feet, NAVD88 (2004.65))*

Location (See Figure 7)	**U.S. Scenario 1**	**Plaintiffs' Scenario 1**	**Observed HWM***
#1	10.9	10.8	--
#2	10.9	10.8	10.5
#3	11.1	10.8	10.0
#4	11.1	10.9	11.9
#5	11.3	11.7	11.0
#6	11.2	11.6	11.0
#7	11.3	12.2	10.5
#8	11.3	12.0	10.0
#9	11.3	10.0	10.8
#10	11.3	9.9	10.8

* Observed high water marks are from the IPET report and represent the higher elevations within the subbasin.

A comparison of the stage hydrographs indicates Plaintiffs' peak water surface elevations occurred in the 9:00 to 11:00 am time frame, while U.S. peaks in the 2:00 to 3:00 time frame. At Jackson Barracks, the peak of 10.5 feet was reported to have occurred about 2:45 pm [IPET IV-196]. Differences in the timing of the peak stage may be due to the differences in the surge stage hydrographs used as input in the models.

7. Conclusions

The interior drainage team developed a hydraulic model of the St. Bernard basin that reasonably replicated the actual Hurricane Katrina water level observations and timing. In addition to running this model with the actual MRGO dimensions and marsh conditions that existed at Katrina's landfall, we ran the model with MRGO at approximate design dimensions and the surrounding marshes in their 1956 condition. Results show that maximum water surface elevations are virtually identical under both of these scenarios.

If the IHNC breaches had not occurred, the maximum water surface elevations would have been about the same in the Lower Ninth Ward, and 0.2 to 0.4 feet lower in the rest of the St. Bernard basin. This indicates how strongly the overtopping and breaching along the MRGO affects the maximum water surface elevations.

8. References

[1] Interagency Performance Evaluation Task Force [IPET, Vol. I], Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Final Report of the Interagency Performance Evaluation Task Force, U.S. Army Corps of Engineers, Volume I Executive Summary and Overview, June 1, 2008

[2] Interagency Performance Evaluation Task Force [IPET, Vol. VI], Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Final Report of the Interagency Performance Evaluation Task Force, U.S. Army Corps of Engineers, Volume VI The Performance – Interior Drainage and Pumping, March 26, 2007

[3] Interagency Performance Evaluation Task Force [IPET, Vol. VI-4], Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Final Report of the Interagency Performance Evaluation Task Force, U.S. Army Corps of Engineers, Volume VI-4 Appendix 4, Interior Drainage Analysis – St. Bernard Parish and the Lower Ninth Ward of Orleans Parish, March 26, 2007

[4] “Analysis of Flooding of the Lower Ninth Ward and St. Bernard Parish, Hurricane Katrina August 2005, New Orleans, Louisiana” CivilTech Engineering, Inc., June 27, 2008

Appendix A – Professional Resume of Steven D. Fitzgerald

Education: 1977-1979 University of Illinois at Champaign-Urbana, M.S.C.E.
1973-1977 Stanford University, B.S.C.E.

Experience: **1981-Present** **Harris County Flood Control District (HCFCD)**
Houston, Texas

Positions Held:

1981-1984 Watershed Coordinator
1984-1989 Manager, Watershed Coordination Department
1989-1997 Manager, Capital Improvements Department
1997-Present Chief Engineer

Highlights:

- Coordinated development and authored most of the HCFCD's first design criteria manual in 1984. Prepared an improved and updated manual in 2004 in coordination with HCFCD staff and community organizations.
- As manager of the HCFCD's first Capital Improvements Department, developed procedures, engineering technical body of knowledge, standard design scopes, project priorities, and budgets.
- Created and currently manages the HCFCD's Flood Watch and Information Program which monitors and evaluates actual flood events.
- As lead HCFCD representative to the U.S. Army Corps of Engineers, works closely with Project Managers to keep Harris County federal projects progressing toward completion.
- Served as a member of the U. S. Army Corps of Engineers' Hurricane Katrina New Orleans Interagency Performance Evaluation Task Force (IPET) as a co-lead of the Interior Drainage Team.

Current Assignments:

- Assist with resolution of technical issues for studies and projects
- Program Manager for U.S. Army Corps of Engineers' Projects
- Manage the comprehensive Urban Stormwater Management Study and other special studies
- Independent Technical Review Panel, USACE/FEMA Joint Texas Coastal Surge Study

1979-1981 Turner Collie & Braden, Inc.; Houston, Texas

Graduate Engineer - supported water resource and bridge studies and projects

Professional: Texas Professional Engineers Registration, No. 55832

Member, American Society of Civil Engineers

Industry Advisory Council, Civil & Environmental Engineering Department, Prairie View A&M University

Board Member and Chair of Flood Management Committee, National Association of Flood and Storm Management Agencies (NAFSMA) – On behalf of NAFSMA,

- Chaired the External Review Panel for the "Decision-Making Chronology for the Lake Pontchartrain & Vicinity Hurricane Protection Project" report prepared for the U.S. Army Corps of Engineers.
- Member of the Review Team for the National Committee on Levee Safety

Publications: Fitzgerald, Steven D. and Holley, Edward R. Holley, "Jet Injections for Optimum Mixing in Pipe Flow," *Journal of the Hydraulics Division,* American Society of Civil Engineers, October 1981, Vol. 107, No. HY10

Wang, KH, Cleveland, T.G., Fitzgerald, S., and X. Ren, "Hydrodynamic Flow Model at the Confluence of Two Streams," *Journal of Engineering Mechanics*, American Society of Civil Engineers, 1996, Vol. 122, No. 10, pp 994-1002

Depositions: Depositions in last four years –

July 17, 2007, *Edward A and Norma Kerr, et al. vs. Harris County Flood Control District and Harris County, Texas*, Civil Court, Cause No. 837,329

Appendix B – Abbreviations and Definitions

Abbreviations

CDT	Central Daylight Time
GIWW	Gulf Intracoastal Waterway
HEC-RAS	Hydrologic Engineering Center - River Analysis System
HEC-HMS	Hydrologic Engineering Center - Hydrologic Modeling System
HWM	High Water Mark
IHNC	Inner Harbor Navigation Canal
ILIT	Independent Levee Investigation Team
IPET	Interagency Performance Evaluation Task Force
LiDAR	Light Detection and Ranging
MRGO	Mississippi River Gulf Outlet
SCS	Soil Conservation Service
USACE	U. S. Army Corps of Engineers

Definitions

Basin	The protected area within a levee system. Also referred to as a polder or bowl.
Breach	Loss of levee crest or top of floodwall elevation during a storm event.
NAVD88 (2004.65)	North American Vertical Datum 1988, 2004.65 adjustment developed during as part of the IPET study to reconcile the various datums, adjustments, and epochs used in New Orleans area.
Overtopping	Water that flows over a levee or flood control structure due to an elevated water level which is higher than the crest level.
Polder	The protected area within a levee system. Also referred to as a basin or bowl.
Stage Hydrograph	The change of water surface elevation at a given point over time due to water levels rising or falling in a channel, canal, or land surface. Can be displayed as a plot or in a table.
Subbasin	A part of a basin delineated based on hydraulic or land features to facilitate analysis of flow into, out of, or through the subbasin. Also referred to as storage areas in HEC-RAS.
Surge Hydrograph	The change of water surface elevation at a given point over time

	due to hurricane storm surge. Can be displayed as a plot or in a table.
Water Depth	Water height above ground level.
Wave Setup	The increase in mean water level caused by wave action.
Wave Overtopping	The discharge over the top of a levee or floodwall that occurs when waves run up the face of a levee or break over a structure.