VI The Performance — Interior Drainage and Pumping

Contents

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Executive Summary

IPET Questions Addressed

Volume VI addresses the performance of the pump stations and interior drainage system of the New Orleans and Southeast Louisiana Hurricane Protection System (HPS). The Interagency Performance Evaluation Task Force (IPET) questions addressed in this volume are listed below. Summary level answers to the questions are also provided with details provided in the remaining part of this volume.

- **Question 3. The Performance. How did the floodwalls, levees, pumping stations, and drainage canals, individually and acting as an integrated system, perform in response to Hurricane Katrina, and why?**
    - The drainage canals and interior drainage system performed well by conveying and storing runoff from rainfall for the pump stations to evacuate from the basins. However, the interior drainage system including the pump stations was overwhelmed from the overtopping and breaching of the levees and floodwalls because of the large water volume and flood elevations reached. Many of the pumping stations were rendered inaccessible, inoperable, or without electrical power.
    - In Plaquemines Parish, St. Bernard Parish, and New Orleans East, the entire basins were overwhelmed by the initial inflow on Monday from the overtopping and breaches. In Orleans East Bank and Jefferson Parish, floodwaters later filled areas in the basin not initially flooded by flowing through the canal and drainage network. This was an undesirable and unintentional consequence.
  - What was the contribution of the pumping stations and drainage system in the unwatering of flooded areas?
    - The Interior Drainage Modeling Teams did not get to extend the HEC-RAS models long enough to simulate the entire unwatering time period. The pumping stations did remove all of the floodwater once the levels fell beneath sea level.

  - What areas or components of the flood protection system have sustained damages that reduce their protection capacity and may need some reconstitution of capacity?
    - Most of the interior canals and storm drain collection systems have been cleared of debris and are ready to convey and store water from rainfall and water that makes it past the HPS.
    - In Jefferson, Orleans, Plaquemines, and St. Bernard Parishes, the total pump capacity was significantly reduced by Hurricane Katrina. Only 16 percent of the combined pumping capacity remained operating during Katrina. Approximately 1/3 of the pump stations and power supply facilities required repairs or rehabilitation to become operational.

- **Question 4. The Consequences. What have been the societal-related consequences of the Katrina-related damage?**
    - This general question is addressed in Volume VII – Consequences.
  - What would the consequences have been if the system would not have suffered catastrophic failure?
    - Table 9 shows the estimated flood elevations for the Katrina event and four hypothetical scenarios. In summary, without breaches (defined as loss of crest elevation), flood levels would have been lower in all basins. The assumption for the pumping capacity is significant and is discussed in the Objectives section below.

Overview

The main report of this volume contains the background, overview, and summary of results for the Interior Drainage System and the Pump Stations. Specific descriptions and results for each basin are contained in Appendices 1–5, 8, and 9, one for each of the parishes. Model sensitivity testing results are shown in Appendix 6. The pump station performance details are given in Appendix 7.

There are two separate tasks in this volume – Interior Drainage Analysis and Pump Station Performance – that address these questions. The pump performance results were incorporated into the interior drainage modeling. The flood levels from the interior drainage modeling were one factor used in the consequences evaluation.

Interior Drainage Analysis

Background

To answer the questions regarding the performance of the HPS, the interior drainage analysis focused on the filling and unwatering of the separate areas protected by levees and pump stations, referred to as basins. Interior drainage models were developed for Jefferson, Orleans, St. Bernard, and Plaquemines Parishes to simulate water levels for what happened during Hurricane Katrina and what would have happened had all the hurricane protection facilities remained intact and functioned as intended.

The primary components of the hurricane protection system are the levees and floodwalls designed and constructed by the Corps of Engineers. Other drainage and flood control features (land topography, streets, culverts, bridges, storm sewers, roadside ditches, canals, and pump stations) work in concert with the Corps levees and floodwalls and are an integral part of the interior drainage and flood damage reduction system and are also included in the models.

Interior drainage models are needed for estimating water elevations inside leveed areas, or basins, for a catastrophic condition such as Hurricane Katrina and for understanding the relationship between HPS components. Results from the interior drainage models can be used to determine the extent, depth, and duration of flooding for multiple failure and non-failure scenarios. The models can also be used to:

- Support the risk modeling effort
- Estimate time needed to unwater an area
- Support evacuation planning
- Evaluate design options of the HPS to include multiple interior drainage scenarios.

Objectives

Develop Interior Drainage Models

The objective discussed herein is to develop interior drainage models that simulate water elevations in Jefferson, Orleans, St. Bernard, and Plaquemines Parishes based on flows into and out of the basins that flooded during Hurricane Katrina. Water enters the areas protected by the HPS from precipitation, levee and floodwall breaches, levee and floodwall overtopping, breaches caused by water flanking structures, and pump backflow. Water flows out of the basins through storm induced and man-made breaches, and pump stations.

The interior drainage models were developed to help answer questions 3 and 4 listed on page 1 of this volume. Question 3 is answered by the Katrina simulation listed below. Question 4 is a more difficult to answer. This is mainly due to the variety of possible combinations of system features, especially pumps. It was decided to bracket these combinations with the four hypothetical scenarios listed below.

One of the major difficulties is determining what pumps may have continued operating. There are many potential factors that can cause pump stations to not operate during a hurricane event. Some of these are power failures, pump equipment failures, clogged pump intakes, flooding of the pump equipment, loss of municipal water supply used to cool pump equipment, and no safe housing for operators at the pump stations resulting in pump abandonment. Because there is such a wide range of possible pumping scenarios that could occur during a hurricane event, it is difficult to establish a pumping scenario for what could have happened. At best, a variety of possible scenarios could be run to evaluate the potential range of possible consequences. For the purposes of the IPET analysis, it was decided to operate the pumps two ways: (1) As they actually operated during hurricane Katrina and (2) how the pumps could have operated throughout the hurricane.

Described below are the five scenarios shown in this report. Results of each are described in Appendices 1 to 5, 8, and 9.

Katrina

Using the interior drainage models, simulate what happened during Hurricane Katrina with the hurricane protection facilities and pump stations performing as actually occurred. Compare results to observed and measured high water marks. Adjust model parameters, as appropriate, to more accurately simulate flood levels and timing. Pre-Katrina elevations are used for top of floodwalls and levees.

Hypothetical 1 – Resilient Levees and Floodwalls

Using the interior drainage models, simulate what would have happened during Hurricane Katrina had all levees and floodwalls remained intact. There are no levee or floodwall breaches or failures for this scenario even where overtopping occurs. Pump stations operate as they did in the Katrina event. Pre-Katrina elevations are used for top of floodwalls and levees. This scenario is meant to simulate what could have happened if all levees and floodwalls had protection that would allow them to be overtopped but not breached.

Hypothetical 2 – Resilient Floodwalls, Levees, and Pump Stations

Using the interior drainage models, simulate what would have happened during Hurricane Katrina had all levees, floodwalls, and pump stations remained intact and operating. There are no levee or floodwall breaches or failures for this scenario even where overtopping occurs. Pump stations operate continuously throughout the hurricane. Pump operations are based on the pump efficiency curves which reflect tailwater impacts. Pre-Katrina elevations are used for top of floodwalls and levees. It is understood, that in their present state, most pump stations would not have been able to stay in operation during Katrina. However, this scenario was simulated to provide an upper limit on what could have been the best possible scenario had no failures occurred.

Hypothetical 3 – Resilient Floodwalls

Using the interior drainage models, simulate what would have happened during Hurricane Katrina had all floodwalls, which failed from foundation failures, remained intact. All other areas are modeled as they actually functioned. Pump stations operate as they did in the Katrina event. Pre-Katrina elevations are used for top of floodwalls and levees. For this simulation there are no failures on 17th Street or London Canals. However, there are failures on the Inner Harbor Navigation Canal (IHNC) since the surge and waves overtopped the walls, exceeding design and resulting in breaches. For the New Orleans East basin, St. Bernard Parish, and Plaquemines Parish, surge and wave heights overtopped levees and floodwalls and, therefore, they were breached the same as during Katrina. In Jefferson Parish, no levees or floodwalls were exceeded during Katrina; therefore there are no failures for this scenario. The result of this scenario for New Orleans East basin, St. Bernard Parish, Plaquemines Parish, and Jefferson Parish, both East and West Bank, is that the inundation matches the inundation for the Katrina simulation. For Orleans East Bank, results of this scenario will differ from the Katrina simulation.

Hypothetical 4 – Resilient Floodwalls and Levees at Authorized Design Grade

Simulate what would have happened during Hurricane Katrina had all levees and floodwalls remained intact and the crest of all levees and floodwalls were at the authorized design grade elevation. There are no levee or floodwall breaches or failures for this scenario even where overtopping occurs. Pump stations operate as they did during the Katrina event.

Table 1 lists the simulation scenarios in a matrix format.

Table 1
Katrina Scenarios

	Katrina	Hypothetical 1	Hypothetical 2	Hypothetical 3	Hypothetical 4
Pumps operate as during Katrina	X	X		X	X
Pumps operate throughout Katrina			X		
Levee and floodwall breaches occur everywhere as during Katrina	X				
Levee and floodwall breaches occur on West wall of IHNC and in, St Bernard, New Orleans East and Plaquemines as during Katrina				X	
Levee and floodwalls overtop but do not breach		X	X		X
No failures on 17th Street and London Ave		X	X	X	X
Levee and floodwall elevations based on pre-Katrina elevations	X	X	X	X	
Levees and Floodwalls elevations are at authorized elevation					X

Team

A team of national experts in interior drainage and pump analysis was assembled to develop the models, run the simulations, and critique the results. All team members worked cooperatively to complete the work within the time required. The team members are listed below.

Interior Modeling Team

Name	Agency	Role
Jeff Harris	USACE – Hydrologic Engineering Center	Co-Lead
Steve Fitzgerald	Harris County Flood Control District	Co-Lead
Gary Brunner	USACE – Hydrologic Engineering Center	Modeling Team
Cameron Ackerman	USACE – Hydrologic Engineering Center	Modeling Team
D. Michael Gee	USACE – Hydrologic Engineering Center	Modeling Team
Matt Fleming	USACE – Hydrologic Engineering Center	Modeling Team
Mark Jensen	USACE – Hydrologic Engineering Center	Modeling Team
James Doan	USACE – Hydrologic Engineering Center	Modeling Team
Clyde Barre	USACE – New Orleans District	Modeling Team
Robert Bass	USACE – New Orleans District	Modeling Team
David Ramirez	USACE – New Orleans District	Modeling Team
Heath Jones	USACE – New Orleans District	Modeling Team
Ed Blodgett	USACE – New Orleans District	Modeling Team
Ron Goldman	USACE – Vicksburg District	Modeling Team
Mike Smith	USACE – Vicksburg District	Modeling Team
Ben Stubbs	USACE – Vicksburg District	Modeling Team
Ron Copeland	USACE – Vicksburg District	Modeling Team
Malcolm Dove	USACE – Vicksburg District	Modeling Team
Mike Trawle	USACE – Vicksburg District	Modeling Team
Chris Nygaard	USACE – Portland District	Modeling Team
Sue Davis	USACE – Chicago District	CTE Contract
Nick Textor	CTE/AECOM	Modeling Team
John Morgan	CTE/AECOM	Modeling Team
Lee Guethle	CTE/AECOM	Modeling Team
Bruce Halverson	CTE/AECOM	Modeling Team

Dan Tornil	CTE/AECOM	Modeling Team
Art Miller	Pennsylvania State University	Interagency Review
Jayantha Obeysekera	South Florida Water Management District	Interagency Review

Pump Performance Team

Name	**Agency**	**Role**
Brian Moentenich	USACE/NWP-HDC	Co-Leader & Main Report
Bob Howard	South Florida Water Management District	Co-Leader & Risk & Reliability
Ken Earlywine	USACE/NWP-HDC	Project Coordinator
Chris Polinsky	USACE/NWP-HDC	Appendix 7 Technical Lead
Kristen Little	USACE/NWP-HDC	Appendix 7
Dan Patla	USACE/NWP-HDC	Appendix 7
James Kiel	USACE/NWP-HDC	Appendix 7
Jennifer Price	USACE/NWP-HDC	Appendix 7
Steve Schlenker	USACE/NWP-EC-HD	Reverse Flow Characteristics
Karen Kuhn	USACE/NWP-EC-HD	Reverse Flow Characteristics
Guy Fielding	USACE/NWP-EC-HD	Reverse Flow Characteristics
Michael Ott	USACE/NWP-EC-HY	Reverse Flow Characteristics
Jim Burton	USACE/NWP-EC-HY	Reverse Flow Characteristics
Sharon Schulz	USACE/NWP-EC-HY	Reverse Flow Characteristics
Kyle McCune	USACE/NWP-EC-HY	ITR
Jim Norlin	HDC Retiree	ITR
Jim Kerr	USACE/NWP-HDC	ITR
Ch2M Hill	Contractor	Data Collection

Study Areas

Eight basins were identified for interior drainage analysis as shown in Figure 1. The six basins completed are listed in Table 2. St. Charles East Bank and West Bank Orleans were not able to be completed within the allotted time. It is recommended that these be completed in the post-IPET effort as discussed in the Post-IPET section.

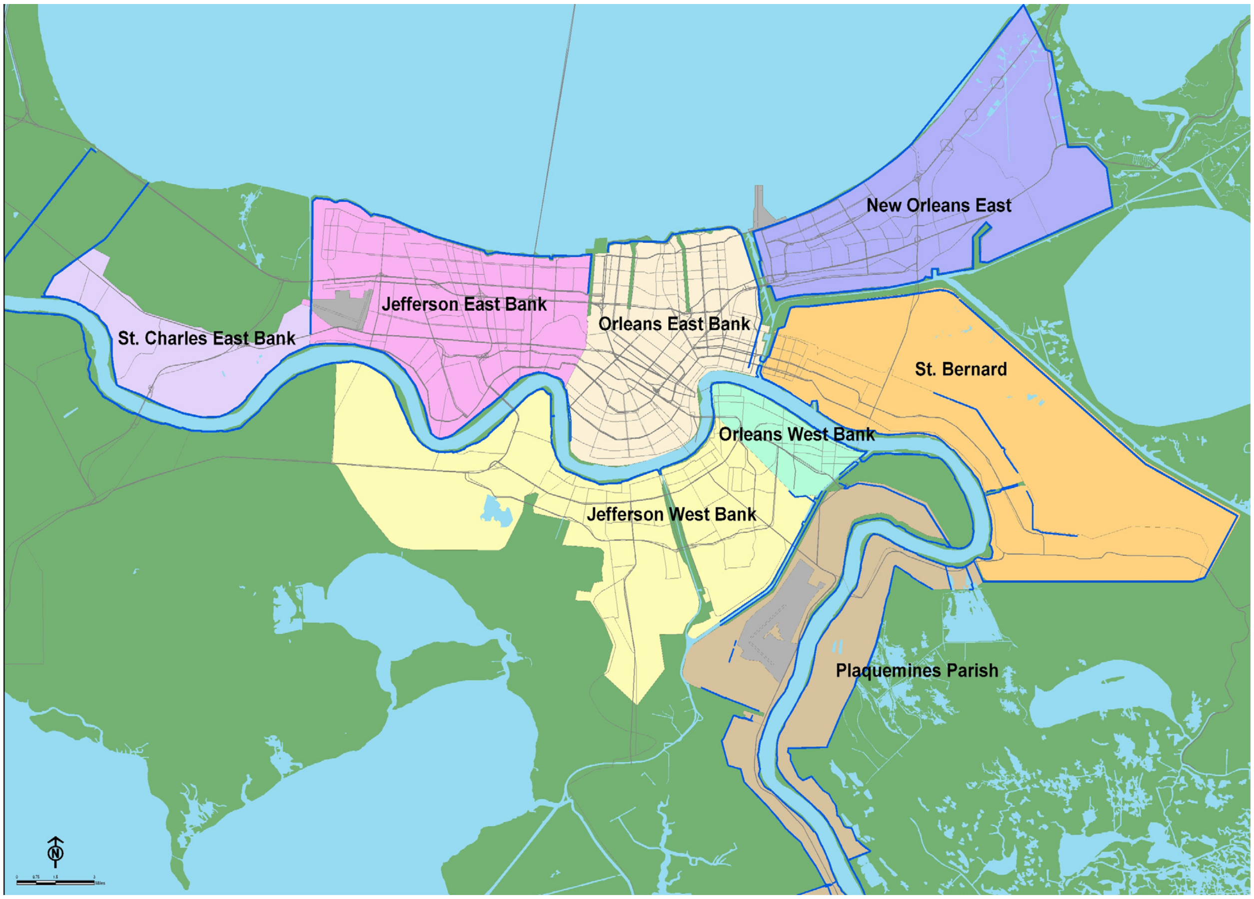

Figure 1. Basin layout and names.

In order to develop good quality models within the time frame required, four teams were utilized to model the basins. Modeling teams were organized based on previous experience and knowledge of the interior drainage system and modeling of the basins. One exception was Plaquemines Parish where previous experience was limited and no previous models existed. The Hydrologic Engineering Center developed models for this parish. Table 2 shows the modeling responsibilities.

Table 2
Completed Basins

Basin	Team	
	HEC-RAS	HEC-HMS
Jefferson East Bank	CTE	CTE
Jefferson West Bank	CTE	CTE
Orleans East Bank	MVK	MVK
New Orleans East	MVN	MVN
St. Bernard	MVN	HEC
Plaquemines	HEC	HEC

CTE – CTE Consultants, Chicago, IL.
MVK – Corps of Engineers, Vicksburg District.
MVN – Corps of Engineers, New Orleans District.
HEC – Corps of Engineers, Hydrologic Engineering Center, Davis, CA.

The HEC-RAS and HEC-HMS models are described below.

Analysis Approach

Models Selected

HEC-RAS and HEC-HMS models were used for this study. These are tools developed by the Corps of Engineers, Hydrologic Engineering Center. HEC-RAS refers to the River Analysis System software package. HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. HEC-HMS refers to the Hydrologic Modeling System software package. HEC-HMS is designed to simulate the precipitation-runoff process. For this study, it is used to transform the precipitation, observed during Katrina, into runoff. This runoff is input to the HEC-RAS model and routed to the pump stations. A description of how these models were used specifically for this study is in the Hydraulic Analysis (HEC-RAS model) and Hydrologic Analysis (HEC-HMS model) sections below.

Input Data

Other IPET task teams provided data needed to estimate the flow into and out of the modeled parishes. Where available, actual or observed data were used, otherwise, model data were used. As expected, actual or observed data were difficult to obtain due to the extent and severity of the hurricane and the resulting flooding.

Table 3 summarizes the data provided by others that were used in the interior drainage models.

Table 3
Input Data Description

General
Digital background maps and GIS layers (USGS digital quads, orthophotos, parcel data, streets and roads)
Time history of observed hurricane system response - surge, flooding, wave heights, levee damage, levee repairs, water level rise and fall within basins
Previous H&H studies; Available H&H models
Aerial photos before and during flood – location and date/time
Geometry
Digital Elevation Models (LIDAR)
Levee and floodwall alignments, profiles, and crest elevations - pre-Katrina and post-Katrina
Surveys and/or as-builts for culverts and bridges
Interior area drainage network data – sizes, locations, profiles
Canal center lines and cross sections
Hydrologic Data
Katrina precipitation data – point and radar
High water elevations and times within basins
Flood inundation maps within basins of Katrina – boundaries and elevations over time
Land use and soil data
Hydraulic Data
Historic stream gauge data, high water marks, and pump station data. Stream gauge rating curves
Katrina surge height hydrographs
Breaches - locations, depth, width, descriptions, photos, and dates and times started, fully developed, and repaired
Landside scour locations
Photos of levee/floodwall breaches, flanking, and overtopping – georeferenced and with date/time
Pump station data - location, number of pumps, pump capacity and curves for each pump, backflow curves, operation plans, Katrina operation timelines
Underground Pipe Network – size, direction, location
Unsteady Flow Options – Priessmann Slot, Theta (0.X), Pumps, pump rules, lateral overtopping, gates

Assumptions

Assumptions were necessary to complete the analysis with satisfactory results in the timeframe required. The assumptions (bold type) and explanations are as follows.

- **Sources known to contribute relatively small volumes of water within the leveed areas were not modeled.** Examples include water blowing over the top of levees and floodwalls, backflow through pumps except in Jefferson East Bank, and any groundwater contribution.

- **Flow in canals (open and enclosed) and through operating pumps was not reduced by debris blockages.** Since the Katrina simulation elevations were reasonably close to the observed elevations, debris probably did not significantly impact the flood elevations. However, debris most likely had more of an impact on the unwatering efforts in some basins.

- **Model only primary internal drainage canals (open and enclosed) and pump stations.** Small canals, collector ditches and storm drains less than 21 inches in diameter were not modeled. Interior canals carrying flow to pump stations were modeled. All outfall pump stations and large interior pump stations were included. with capacities generally larger than 5 percent of the total pump capacity of the basin.

- **Pumps operate either as they actually performed during Katrina or they operated continuously based on pump efficiency curves.** The reason for selecting these two pumping conditions is explained above in the Objectives section.

Model Development Sequence

Development of the models for each basin followed the following sequence:

1. Develop HEC-HMS models using existing models, if available. Otherwise, construct new HMS models.

2. Develop HEC-RAS models by updating existing models to reflect conditions at the time of Katrina, if available, or constructing new RAS models where none existed.

3. Conduct a sensitivity evaluation of critical model parameters.

4. Run the Actual Performance Simulation results using Katrina storm data and summarize the results. Adjust model parameters, as appropriate, to more accurately simulate flood levels and timing.

5. Run the No-Breach Simulation and summarize the results.

Hydrologic Analysis (HEC-HMS Model)

Introduction

HEC-HMS models were developed for each basin and correspond directly with the HEC-RAS model for the basin. The HEC-HMS subbasin boundaries are the same as the HEC-RAS storage area boundaries. This approach allows the HEC-HMS model to transform the Katrina precipitation into computed runoff hydrograph that is input to HEC-RAS as inflow to a storage area.

Rainfall

Radar rainfall data for the Katrina event was obtained from the Lower Mississippi River Forecast Center (National Oceanic and Atmospheric Administration, NOAA). Radar data were adjusted using rain gauge measurements and other sources to produce the final estimate. Figure 2 shows the total rainfall amounts for Hurricane Katrina. The radar rainfall data were imported into GIS where available tools were used to generate a precipitation hyetograph for each HEC-HMS subbasin.

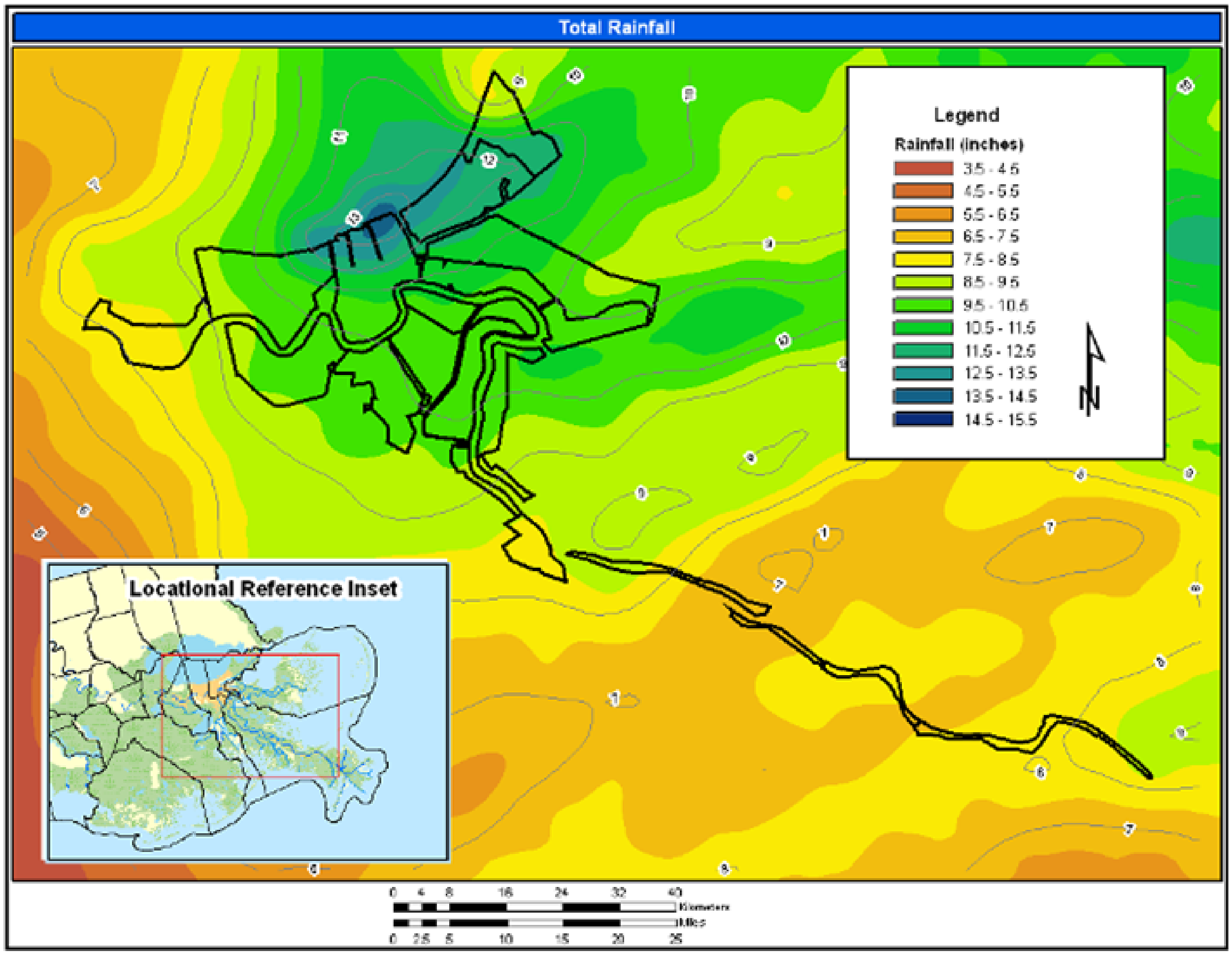

Figure 2. Total rainfall, Hurricane Katrina event, 28-29 August 2005.

A comparison of Hurricane Katrina rainfall to previous tropical (and one non-tropical) events in the New Orleans area is shown in Table 4.

Table 4
Rainfall Comparison

Storm	Year	Total Storm Rainfall Range (inches)
Hurricane Katrina	2005	8.0 - 14.0
Tropical Storm Isidore	2002	4.5 - 7.5
Hurricane Lili	2002	2.5 - 8.5
Tropical Storm Allison	2001	14.5 - 21.5
Hurricane Danny	1997	1.0 - 9.5
May 8-10, non-tropical	1995	10 - 24
Hurricane Andrew	1992	5.6 - 6.0
Hurricane Betsy	1965	4.0 - 7.0

The frequency of the 24-hour rainfall from Katrina varied across the New Orleans region. Katrina values ranged from 8 to 14 inches. Table 5 shows the range over the region and Table 6 shows the range of rainfall frequencies over the area. Rainfall frequency values were estimated from charts in National Weather Service Technical Paper No. 40.

Table 5
Katrina 24-Hour Precipitation Values

Area	Katrina 24-Hr Precipitation Range (inches)
Jefferson Parish	9 - 12
Orleans East Bank	10 - 15
New Orleans East	8 - 14
St. Bernard	7 - 12
Plaquemines	7 - 10

Table 6
TP-40 24-Hour Precipitation Frequency

Event	TP-40 24-Hr Precipitation Range (inches)
2-Year	5.5 – 6.0
5-Year	7.5 – 8.5
10-Year	9 – 10
25-Year	10 – 12
50-Year	11 – 13
100-Year	13 - 15

Loss Rates

Loss rates were computed by determining the amount of precipitation intercepted by the canopy and depressions on the land surface and the amount of precipitation that infiltrated into the soil. Precipitation that is not lost to interception or infiltration becomes excess precipitation or direct runoff. The Soil Conservation Service (SCS) Curve Number (CN) method was used to model interception and infiltration. The SCS CN method estimates precipitation loss and excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture. This method uses a single parameter, a curve number, to estimate the amount of precipitation excess/loss from a storm event.

Land use data were obtained from the New Orleans District (MVN) and consisted of a raster coverage of 24 different land use types. Soil data were obtained from the National Resources Conservation Service (NRCS). The data on the NRCS website is referred to as the Soil Survey Geographic (SSURGO) Database and is a digital copy of the original county soil survey maps.

Runoff Hydrograph

Excess precipitation was transformed to a runoff hydrograph using the SCS unit hydrograph method option in HEC-HMS. The drainage area of each subbasin was computed using GIS and input into HEC-HMS. Lag time was computed by using an estimate of travel time for the longest flow path within the subbasin.

A sample result from one subbasin is shown in Figure 3. The upper graph shows the total precipitation and excess precipitation. The lower graph shows the runoff hydrograph from the subbasin that is entered in the HEC-RAS model as rainfall inflow.

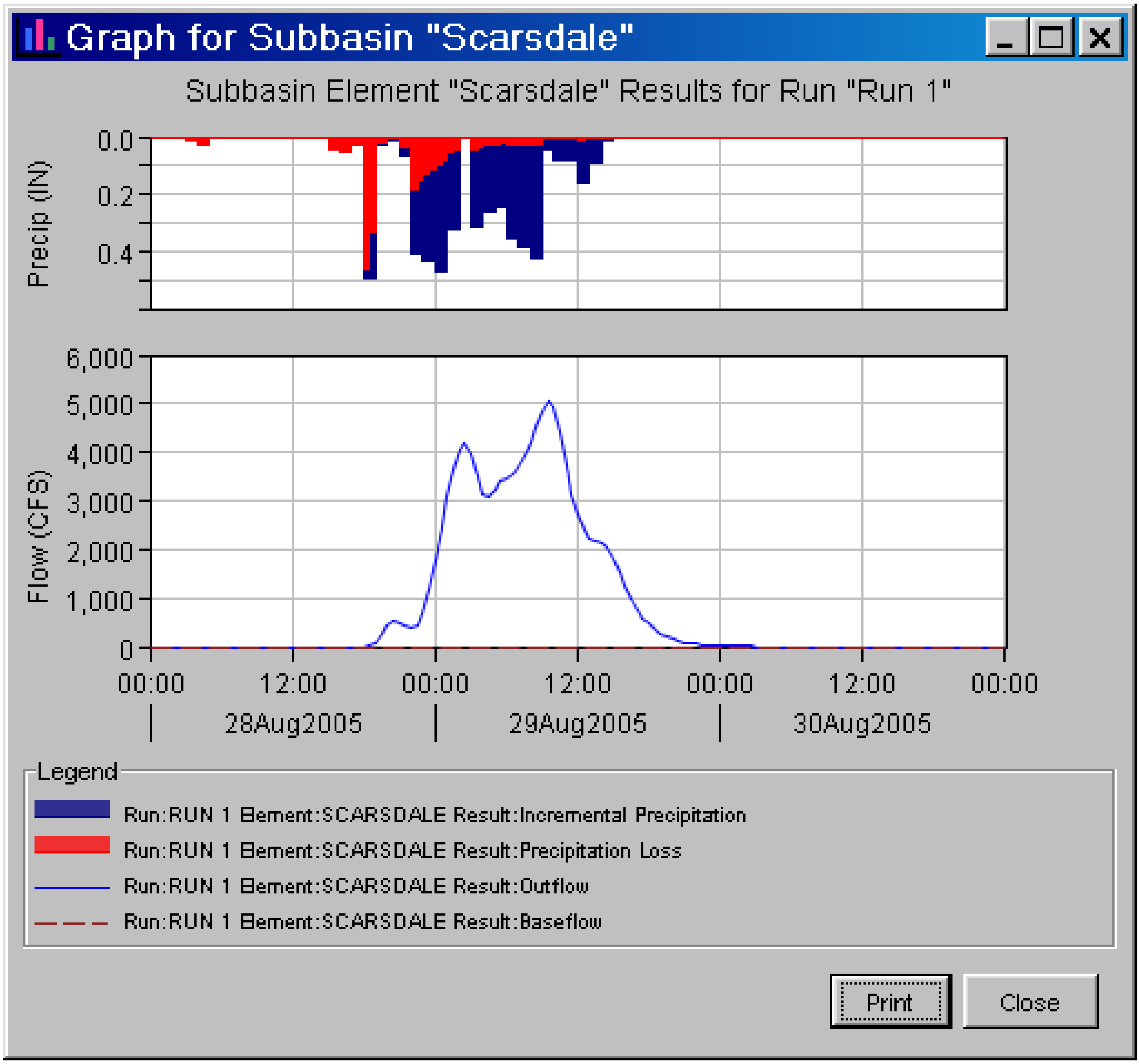

Figure 3. HEC-HMS subbasin results.

Hydraulic Analysis (HEC-RAS Model)

Introduction

HEC-RAS models were developed for each basin and were run independently in accordance with the current drainage patterns within the greater New Orleans area. Each parish maintains their own drainage system and the models reflect this operation. Volume III summarizes the interior drainage system of each basin, its design criteria, and its condition prior to Katrina.

Figure 4 and Table 7 provide the model areas, lists their names, and whether an existing HEC-RAS model was updated or a new HEC-RAS model developed. The HEC-RAS discussion below is general in nature. Information on the individual HEC-RAS models for each modeled area is included in Appendices 1 through 5, 8, and 9, in this volume.

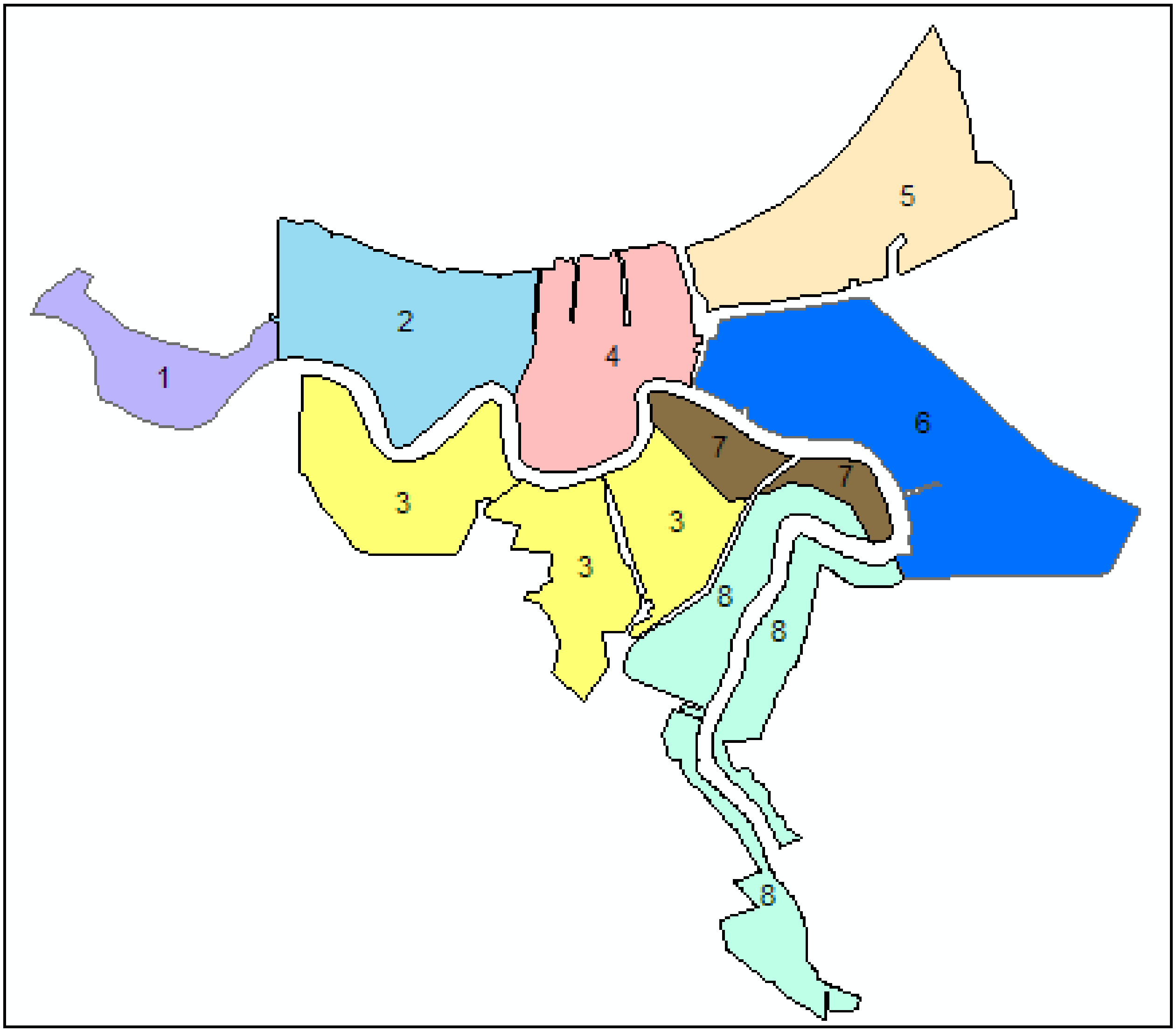

Figure 4. Modeled areas.

Table 7
Model Area Names

Basin Number	Name	RAS Model Development
1	St. Charles East Bank	New
2	Jefferson East Bank	Updated existing
3	Jefferson West Bank (3 subareas, 4 models) a. Bayou Segnette b. Ames-Westwego c. Harvey-Estelle-Cousins d. East of Harvey	Updated existing
4	Orleans East Bank (overflow into Jefferson East bank included)	New
5	New Orleans East	Incorporate existing, build new
6	St. Bernard Parish (Includes Lower 9th Ward in Orleans Parish)	Incorporate existing, build new
7	Orleans West Bank	New
8	Plaquemines Parish (entire area downstream to Venice)	New

Terrain & Datum

The terrain, or ground topography, used in all the HEC-RAS models is based on 5-m LIDAR data set generated in 2001. The datum of the LIDAR is NAVD88 (1994, 1996 epoch). The vertical accuracy for these data is +/- 0.7 ft. The horizontal projection is Louisiana State Plane South 1983 feet. All models have been georeferenced to this projection. The basin boundaries for the HEC-HMS models are in the same projection. Figure 5 shows the topographic layout of the New Orleans area. Topographic layouts for each basin are in their respective appendices.

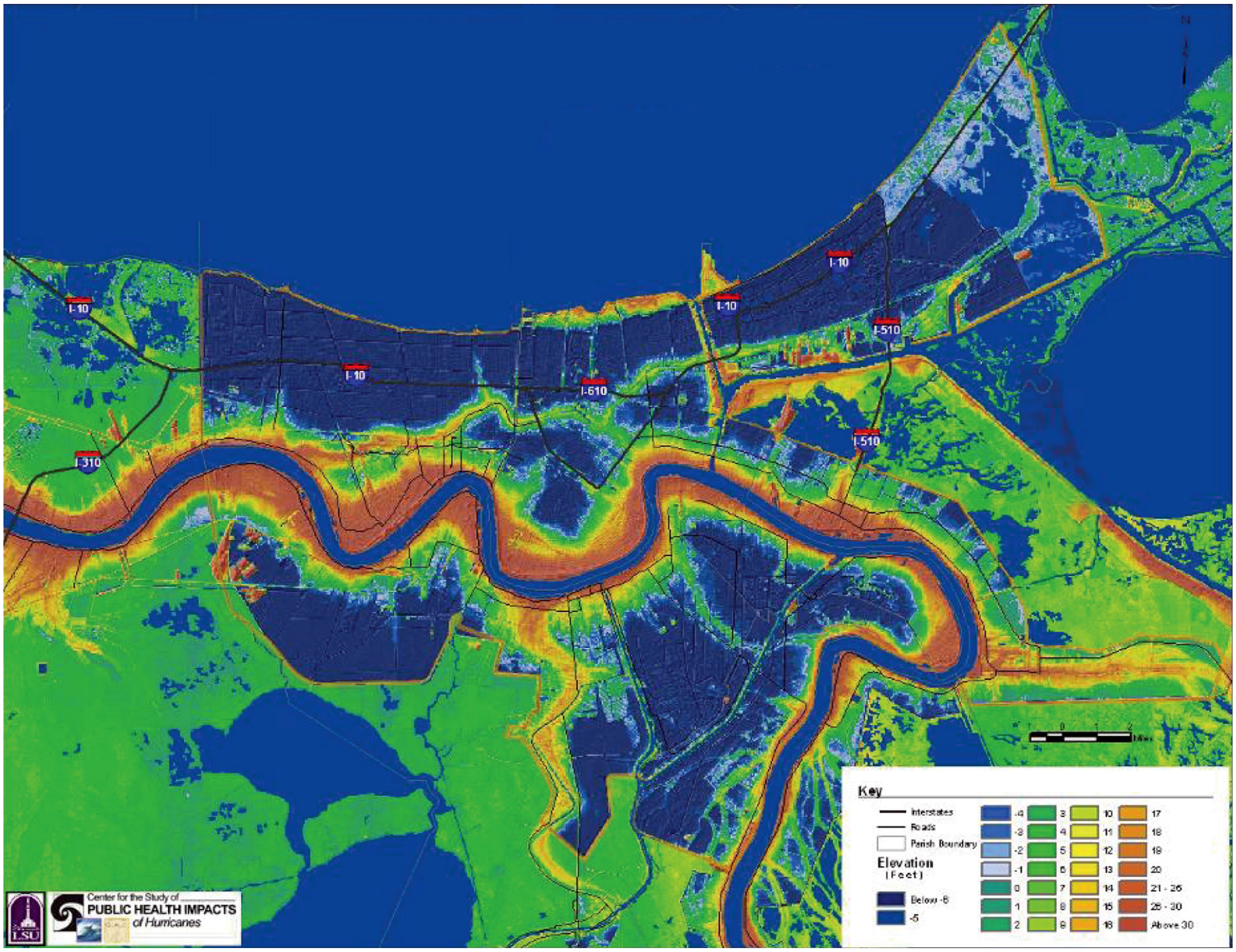

Figure 5. Topographic layout of New Orleans area (generalized elevations, no datum).

After the HEC-RAS models were initially developed and tested, adjustment relationships between the datum and epoch adopted for the IPET study, NAVD88 (2004.65), and historic datum were established by the IPET Geodetic Vertical Datum Team. Because the differences ranged from -0.2 to -0.7 ft and were not consistent within a basin, it was decided not to bring the HEC-RAS models up to the NAVD88 (2004.65) datum. The effort and time required would not improve the accuracy of the modeled water surface elevations.

In St. Bernard Parish, no LIDAR data were published for the Martello Castle NW quarter quadrangle. The terrain data for this quad were derived from other data sources. In particular, intensity values from a high-resolution photo of Martello Castle NW were used. The color intensity values were mapped to a range of elevations from a small area of neighboring LIDAR. Additional discussion can be found in the St. Bernard appendix.

Levees

The physical data for the pre-Katrina levees were obtained from the 2001 5-m LIDAR dataset. All were in the NAVD88 (1996, 1996 epoch) datum.

Floodwalls

The physical data for the pre-Katrina floodwalls were obtained from the 5-m and 2-ft LIDAR surveys. The data for 17th Street, London, and Orleans Canals were incomplete since the top of the floodwall profile did not exist at the breaches. However, since these walls did not overtop, this was not a critical lack of data. The top of the IHNC floodwall was surveyed and a top of floodwall profile was generated. This profile was used to determine when water began to flow over the top of the floodwall.

Storage Areas

To accurately model the interior drainage system of each basin, subdrainage areas (subbasins) were delineated based on geographic features. These are referred to as storage areas in HEC-RAS. Features used as divisions between storage areas include levees, railroads, roads, elevated areas, and natural high ground. The storage area elevation-volume data and the connection between the storage areas in the RAS models were developed using the HEC-GeoRAS software. GeoRAS is an ArcMap extension. It provides the tools to draw a polygon representing the storage basin shape and then extract the volume-elevation data from the 5-m grid. Additionally, it also provides the tools to draw a line which represents the connection between adjacent storage basins and then extract a profile of the connection that represents the elevations from the 5-m grid. Each RAS model includes storage areas and connections between storage areas (flow diversions).

Water can flow between storage areas through storage area connections. These connections are modeled hydraulically using either a weir equation or a linear routing method to transfer flow between the storage areas. Flow can go in either direction, and submergence on the 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.

Overland Flow

Overland flow is a major component of an interior drainage system whether the source of water is from rainfall, levee overtopping, levee breaches, or pump backflow. The path and amount of overland flow is influenced by the ground topography, levees, elevated areas, roadways, railroads, buildings, fences, etc. Overland flow within the basins eventually ends up in storm sewers, roadside ditches, or canals. HEC-RAS models overland flow using the terrain data and storage areas described above.

Storm Drains

The drainage system for many areas in New Orleans consists of many features that are typical of large urban cities in the United States, and some features that are unique because much of the area is below sea level. As in any urbanized area, catch basins and drop-inlets receive surface runoff from yards and streets, and excess runoff runs down slope in the streets and/or overland to areas of lower elevation. Runoff that can enter drop-inlets proceeds underground in small pipes, 21 in. or less in diameter, called the tertiary system that collect local flows and convey them to the secondary system, 21 in. to 30 in. in diameter, where several of these local flows combine. Generally pipes or box culverts that are larger than 30 in. in diameter are considered to be part of the secondary system. The primary drainage system is composed of enclosed culverts and man-made, mainly prismatic open channels. The primary conveyances, specified in the next section as Interior Canals, were modeled in the HEC-RAS unsteady model, along with drainage pump stations.

Interior Canals

Main storm drains empty into either open or enclosed canals. These canals are referred to as interior canals because they convey water within the basin and to differentiate them from the outfall canals that convey water from the outfall pump stations to Lake Pontchartrain, the IHNC, or Lake Borgne.

The dimensions and slopes of the main interior canals were obtained from drainage system maps, as well as previous models of the storm drainage system. Significant secondary interior canals were added by putting in lateral structures in HEC-RAS along with the main storm drain pipes. The lateral structures, modeled as culverts, were directly connected to surface storage areas that are being used to represent the surface terrain. With this setup, any water in a surface storage area can enter the storm drains through the culverts. Additionally, water that backs up within any storm drain can also flow out into the surface areas through these culverts.

Cross-section data are used to represent the open and enclosed canals. Information for describing the cross sections has come from many sources. General terrain for the open canals is a combination of the terrain data model and surveyed cross-section data. In general, the terrain model does not provide enough detail to hydraulically describe the canals. Additionally, the terrain model does not include any elevation data below the water surface. Surveyed cross-section data have come from previous studies as well as newly surveyed cross sections.

Enclosed canals are modeled in HEC-RAS as normal cross sections with lids to represent a pressurized pipe. HEC-RAS has a feature called the Priessmann Slot option that allows the open channel flow equations to mimic pressure flow equations for an enclosed cross section. The Priessmann Slot option puts a small slot in the lid of the cross section to allow the water surface to rise to the hydraulic gradeline within the pipe. This slot is extremely small and the wetted perimeter of the slot is not included in the conveyance calculations for the storm drain. The width of the slot is calculated in order to get the open channel flow wave celerity to be equal to the pressure wave celerity. This capability allows the HEC-RAS model to handle both open channel flow and pressure flow within a storm drain using the same set of equations.

The interior canals not only collect stormwater from streets and storm drains and convey it to the pump stations, they also provide in-line storage for consideration in the pump station operations.

Pump Stations

With most of the land below sea level in the New Orleans area, pump stations are needed to pump stormwater out of the basins and into an adjacent water body. These are referred to in this report as outfall pump stations. Due to the topography, storm sewer system, and canal layout, pump stations are also used within the interior drainage system to ultimately move stormwater to the outfall pumps. These pump stations are referred to in this report as interior lift stations.

Pump station data were collected by the IPET Pump Station team in the five parishes for all pump stations that pump more than 600 to 800 cfs, depending on the parish. The pump data are described in Appendix 7 of this volume. The data collected that were incorporated in the interior drainage analysis included configuration, capacity, and location of each of the pump stations, pump performance curves, operation plans, records of operation during Katrina, fuel and/or power sources, backflow prevention devices, and valves and gates for operations.

HEC-RAS uses an in-line structure to represent the pump house within a canal. A series of pumps are then added to pump water from the suction side to the discharge side of the structure for the outfall pump stations. These can discharge into an outfall canal or body of water. A similar approach is used for the interior lift stations, except they pump into an open or enclosed interior canal. The HEC-RAS pump option was utilized to model pumps of different sizes, capacities, and different on and off elevations that represent the normal operations of the pumps. Additionally, HEC-RAS has the ability to enter pump override rules. These rules were used to mimic the stopping and starting of pumps due to power failures or pump house flooding that occurred during Katrina.

Outfall Canals

In the Orleans East Bank, the outfall pump stations pump into outfall canals that carry the water two to three miles to Lake Pontchartrain. These canals, 17th Street, London, and Orleans, are long enough that when pump rates are high, the water level at the pump station is higher than the water level at the mouth. When water levels are high at the pump stations, it reduces the pumping capacity of the pumps.

The elevation in the outfall canal impacts the pumping efficiencies, so water levels are calculated in the HEC-RAS model. In addition, the canals are a boundary condition with stage hydrographs resulting from the hurricane calculated using the ADCIRC model (see Volume III).

Inflows

The primary inflows in all of the basins during Katrina were rainfall, levee and floodwall overtopping, and levee and floodwall breaches (including breaches caused by water flanking structures). Backflow through pumps was an apparent major contributor to flooding in Jefferson East Bank, so it was included as an inflow in that model only and is described in Appendix 1 of this Volume.

Prior to adding inflow into the basin, initial conditions were established by putting a base flow in all of the storm sewers and canals. Then, a backwater profile is computed to get the initial water surface. Just upstream of the pump station, the water surface is actually much lower in the sump area than it is on the open canal side. To accommodate this, the option in HEC-RAS was incorporated where one can input a water surface to be used in the backwater computations. Initially, all of the storage areas are dry. This is simulated by setting the starting water surface elevation to the minimum elevation in each of the storage areas.

Rainfall

Initially, it was assumed the contribution of rainfall to the flooding was relatively insignificant compared to the levee and floodwall overtopping and breaches. However, with the estimated total rainfall amount being 8 to 14 inches over 24 hours, it was more significant than originally thought.

HEC-HMS was used to transform rainfall into runoff within each basin. The HEC-HMS computed runoff is input into the HEC-RAS model. A summary of how this is accomplished with HEC-HMS is presented in the Hydrologic Analysis (HEC-HMS Model) section.

Levee and Floodwall Overtopping

The storm surge and wave runup on the exterior levees and floodwalls were provided by the IPET Storm Hydrodynamics Team. The ADCIRC model was used to develop stage hydrographs as input into the HEC-RAS model along the exterior boundary of the basins. The ADCIRC modeling and results are described in Volume IV of this report. Stage-hydrographs are applied directly to the canals that are open to Lake Pontchartrain, Lake Borgne, IHNC, and the Mississippi River. To apply the ADCIRC results in areas that were not modeled as canals (for example, the levees along Lake Pontchartrain and the back levees for New Orleans East and St. Bernard Parish), it was necessary to put in model reaches with cross sections representing the lake areas. Stage hydrographs from ADCIRC were applied to each of these model reaches. In some cases the ADCIRC stage-hydrographs are adjusted to better match high-water marks. For example, Figure 6 shows the stage-hydrograph used as a boundary condition for the 17th Street Canal at Lake Pontchartrain. Each reach is connected to the interior area by using the lateral structure option in HEC-RAS. These lateral structures represent the levees that separate the interior areas from the unprotected exterior areas. The lateral structure option in HEC-RAS allows the model to calculate overtopping flows, as well as any levee breaches that occurred along these levees, using the weir equation.

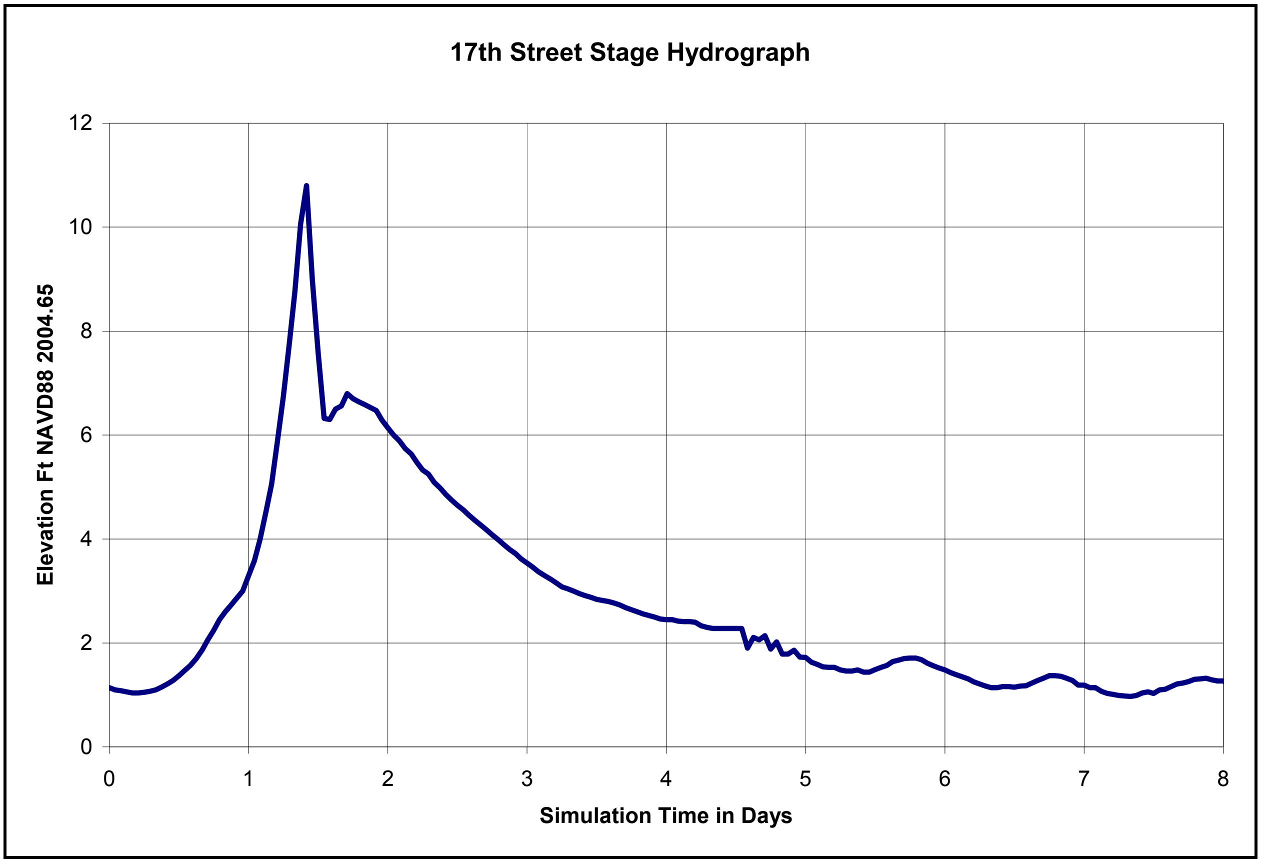

Figure 6. ADCIRC stage-hydrograph for 17th Street Canal at Lake Pontchartrain.

Wave Overtopping

Wave overtopping generated large inflows to St. Bernard Parish and New Orleans East basin. Some exterior levees suffered extensive damage from breaching and wave overtopping during the hurricane. In St. Bernard Parish, damage occurred over 7 miles along the IHNC (Inner Harbor Navigation Canal), GIWW (Gulf Inner Coastal Waterway), and the MRGO (Mississippi River Gulf Outlet). Exterior stages were high enough to overflow the levees and floodwalls at locations along the MRGO and the IHNC. In New Orleans East, wave overflow occurred across the Lake Pontchartrain, MRGO, and GIWW Levees. The wave overtopping component has been estimated and is included as inflow in the HEC-RAS models. Orleans East Bank area experienced wave overtopping in the vicinity of the IHNC. This overtopping is included in the Orleans East Bank analyses. Plaquemines Parish also experienced wave overtopping. However, these data were not available to add to the analyses. Therefore, adjustments were made to the boundary conditions to simulate wave impacts. Detail on this is included in the appropriate appendix.

Levee and Floodwall Breaches

Levee and floodwall breaches are modeled as lateral structures along the canals and lake areas. The top of the levee is the top of the lateral structure. Flow over this structure is modeled with the weir equation. A levee breach can be added to any lateral structure. The breach can be triggered based on a water surface elevation, time, or elevation and duration above an elevation. HEC-RAS requires entering the maximum breach size and duration of the breach development. Breach information was provided by another IPET team. This information was used to estimate the breach parameters used in the HEC-RAS model.

Outflows

Flow out of the flooded basins during Katrina occurred through the storm-induced breaches, deliberate breaches, and/or pumps. Table 8 shows the primary outflow for each basin.

Table 8
Basin Outflow

Basin	Outflow
Orleans East Bank	Storm breaches, pumping
New Orleans East	Storm breaches, pumping
Jefferson East Bank	Pumping
St. Bernard Parish	Storm and deliberate breaches, pumping
Plaquemines Parish	Storm breaches, pumping
Jefferson West Bank	Pumping
Orleans West Bank	Pumping
St. Charles East Bank	Pumping

The recession or outflow was modeled through 1 September 2005. The models did not extend until the unwatering was complete on approximately 15 September and, therefore, do not include any deliberate breaches.

Pumping

The operation records during Katrina collected by the IPET Pump Team from each pump station were used in the HEC-RAS models to simulate the outflow through the pump stations. Many of the stations remained operational during the initial part of the storm, but eventually nearly all shut down due to loss of power or flooding of the station itself. The pumps at the pump stations that were able to be started afterwards significantly contributed to the unwatering. The temporary pumps installed to assist the unwatering were not able to significantly reduce the water levels because of the large volume. See Appendix 7 of this volume for information about the pump stations in each basin.

Levee and Floodwall Breaches

Levee and floodwall overtopping and failures were included in the HEC-RAS models. The timing, duration, and size of the failures collected by the IPET Data Collection Team were used as the parameters for the overtopping and failures. They are modeled as lateral structures connected to storage areas. Details on this can be found in Appendix 1 through 5 of this volume.

Sensitivity Analysis

Sensitivity analysis of various model parameters was conducted. This information is included in Appendix 6.

Summary of Results

The interior drainage models, HEC-RAS and HEC-HMS, were run for each basin for the four simulation scenarios listed below:

Katrina

Using the interior drainage models, simulate what happened during Hurricane Katrina with the hurricane protection facilities and pump stations performing as actually occurred. Compare results to observed and measured high-water marks. Adjust model parameters, as appropriate, to more accurately simulate flood levels and timing. Pre-Katrina elevations are used for top of floodwalls and levees.

Hypothetical 1 – Resilient Levees and Floodwalls

Using the interior drainage models, simulate what would have happened during Hurricane Katrina had all levees and floodwalls remained intact. There are no levee or floodwall breaches or failures for this scenario even where overtopping occurs. Pump stations operate as they did in the Katrina event. Pre-Katrina elevations are used for top of floodwalls and levees. This scenario is meant to simulate what could have happened if all levees and floodwalls had protection that would allow them to be overtopped but not breached.

Hypothetical 2 – Resilient Floodwalls, Levees, and Pump Stations

Using the interior drainage models, simulate what would have happened during Hurricane Katrina had all levees, floodwalls, and pump stations remained intact and operating. There are no levee or floodwall breaches or failures for this scenario even where overtopping occurs. Pump stations operate continuously throughout the hurricane. Pump operations are based on the pump efficiency curves which reflect tailwater impacts. Pre-Katrina elevations are used for top of floodwalls and levees. It is understood, that in their present state, most pump stations would not have been able to stay in operation during Katrina. The reason for this is because most stations are manually operated (i.e. operators must be physically present) and most parishes sent their operators to safe havens before or during Katrina. However, this scenario was simulated to provide an upper limit on what could have been the best possible scenario had no failures occurred.

Hypothetical 3 – Resilient Floodwalls

Using the interior drainage models, simulate what would have happened during Hurricane Katrina had all floodwalls, which failed from foundation failures, remained intact. All other areas are modeled as they actually functioned. Pump stations operate as they did in the Katrina event. Pre-Katrina elevations are used for top of floodwalls and levees. For this simulation there are no failures on 17th Street or London Avenue Canals. However, there are failures on the IHNC since the surge and waves overtopped the walls, exceeding design and resulting in breaches. For the New Orleans East basin, St. Bernard Parish, and Plaquemines Parish, surge and wave heights overtopped levees and floodwalls and, therefore, they were breached the same as during Katrina. In Jefferson Parish, no levees or floodwalls were exceeded during Katrina; therefore, there are no failures for this scenario. The results of this scenario for New Orleans East basin, St. Bernard Parish, Plaquemines Parish, and Jefferson Parish, both East and West Bank, is that the inundation matches the inundation for the Katrina simulation. For Orleans East Bank, results of this scenario will differ from the Katrina simulation.

Hypothetical 4 – Resilient Floodwalls and Levees at Authorized Design Grade

Simulate what would have happened during Hurricane Katrina had all levees and floodwalls remained intact and the crest of all levees and floodwalls were at the authorized design grade elevation. There are no levee or floodwall breaches or failures for this scenario even where overtopping occurs. Pump stations operate as they did during the Katrina event.

Table 9 compares the peak water elevations, depths and surface areas. Ranges are given for each basin since peak water elevations and depths vary within each basin. Elevation and depth ranges may appear inconsistent when compared to each other. However, these values are approximated ranges based on model results and reflect impacts of the various assumptions in each simulation. Please refer to appendices 1 through 5 for detailed results for all areas listed in the Basin column in Table 9.

Table 9
Peak Water Elevation in Feet (NAVD88, 1994-1996 epoch)

Basin		Katrina		Hyp 1	Hyp 2	Hyp 3	Hyp 4
		Modeled	Observed*				
Orleans East Bank	Elevation	2.7 to 4.9	2.5 to 4.7	-3.1 to 4.4	-6.4 to 4.2	-2.4 to 4.9	-6.0 to 4.0
	Depth (ft)	1.0 to 8.0	1.0 to 8.0	1.0 to 7.0	0 to 6.0	1.0 to 7.0	0.0 to 4.0
	Surface (ac)	21,400	21,000	15,000	10,000	16,200	11,000
New Orleans East -							
North of Chef Menteur Hwy	Elevation	-1.2 to 1.4	-1.2 to 1.4	-2.1 to 0.3	-3.8 to 0.2	-2.4 to 4.9	-3.8 to 0.2
	Depth (ft)	2.5 to 9.0	2.5 to 9.0	2.0 to 6.5	2.0 to 6.5	2.5 to 9.0	0.5 to 6.0
	Surface (ac)	22,700	22,000	22,000	21,200	22,700	17,600
South of Chef Menteur Hwy	Elevation	4.2 to 7.9	4.2 to 7.9	-2.7 to 7.5	-3.0 to 7.4	4.2 to 7.9	-3.5 to 7.5
	Depth (ft)	2.5 to 9.0	2.5 to 9.0	2.0 to 7.0	2.0 to 7.0	2.5 to 9.0	1.0 to 8.0
	Surface (ac)	10,300	10,000	9,500	9,400	10,300	8,500
Jefferson East Bank	Elevation	-12.5 to -2.9	-13.9 to -2.9	NA	-12.8 to -3.1	NA	NA
	Depth (ft)	0.0 to 2.5	0.0 to 2.5	NA	0.0 to 3.0	NA	NA
	Surface (ac)	14,500	14,500	NA	4,300	NA	NA
St. Bernard Parish	Elevation	10.8 to 11.9	9.7 to 10.7	3.8 to 6.9	2.7 to 6.9	10.8 to 11.9	2.0 to 6.0
	Depth (ft)	7.0 to 12.5	7.0 to 12.5	3.0 to 7.0	3.0 to 7.0	7.0 to 12.5	2.0 to 6.0
	Surface (ac)	48,400	48,000	44,900	44,700	48,400	36,900
Plaquemines Parish	Elevation	10.1 to 16.9	11.9 to 16.2	10.1 to 16.1	10.1 to 16.0	10.1 to 16.9	10.1 to 14.0
	Depth (ft)	3.0 to 15.0	3.0 to 15.0	3.0 to 15.0	3.0 to 15.0	3.0 to 15.0	1.0 to 11.0
	Surface (ac)	41,000	41,000	41,000	41,000	41,000	37,000
Jefferson West Bank -							
Bayou-Segnette	Elevation	-3.3 to -10.0	-3.3 to -10.0	NA	-5.7 to -10.7	NA	NA
	Depth (ft)	0.0 to 3.5	0.0 to 3.5	NA	0.0 to 2.5	NA	NA
	Surface (ac)	3,300	3,300	NA	2,600	NA	NA
Ames-Westwego	Elevation	-1.8 to 1.2	-0.7 to 2.0	NA	-6.3 to -3.8	NA	NA
	Depth (ft)	0.0 to 4.0	0.0 to 4.0	NA	0.0 to 0.7	NA	NA
	Surface (ac)	1,500	1,500	NA	110	NA	NA
Harvey-Estelle-Cousins	Elevation	0.8 to -11.1	0.4 to -11.9	NA	-0.3 to -11.3	NA	NA
	Depth (ft)	0.0 to 3.0	0.0 to 3.0	NA	0.0 to 1.5	NA	NA
	Surface (ac)	4,500	4,500	NA	180	NA	NA
East of Harvey	Elevation	-3.1 to -3.2	-3.7 to -5.7	NA	-9.4 to -4.0	NA	NA
	Depth (ft)	0.0 to 3.0	0.0 to 3.0	NA	0.0 to 1.5	NA	NA
	Surface (ac)	5,700	5,700	NA	850	NA	NA

- Variations in observed peak water elevations are expected due to the difficulty in physically identifying the highest water level after the event. The water stains or mud lines commonly seen are usually not the peak elevation, but rather the elevation where the water stayed over an extended period of time. Observed surface area values are estimated.
- NA – Value not applicable since the hypothetical scenario does not apply to that area.

The model results are in close agreement with the observed peak water elevations, most are within a 0.5 feet. The No-Breach simulation results show water level reductions the greatest in the subbasins near where the major breaches occurred.

Table 10 lists the total volume of water, and the percent contribution by source, for each simulation. The pump backflow volume shown for Jefferson East Bank is an estimate based on rating curves developed by the Pump Performance Team and ADCIRC computed stage hydrographs in Lake Pontchartrain. It is possible that the volume contributed by backflow could be higher.

Table 10
Hurricane Katrina Volume

Basin	Total Volume Acre-feet	Percent Contribution			
		Rainfall	Over topping	Breaches	Pump Backflow
Orleans East Bank	85,000	26	16	58	NA
New Orleans East	142,000	13	70	17	NA
Jefferson East Bank	23,500	88	0	0	12
St. Bernard Parish	429,000	8	29	63	NA
Plaquemines Parish	155,000	16	69	15	NA
Jefferson West Bank	31,500	100	0	0	NA

NA – Not Applicable.

One of the questions the Interior Drainage Analysis Team had hoped to help answer was, “What was the contribution of the pumping stations and drainage system in the unwatering of flooded areas?” The Modeling Teams did not get to extend the HEC-RAS models long enough to simulate the entire unwatering time period. The pumping stations did remove all of the floodwater once the levels fell beneath sea level.

Lessons Learned

1. **Maintain current hydrologic (like HEC-HMS) and hydraulic (like HEC-RAS) models for flood forecasting and post-flood evaluations.** Water levels inside basins can be estimated prior to a tropical system hitting the New Orleans area to help the authorities and the public make decisions. After the storm, the models can be used to estimate the unwatering time, if necessary.

2. **Install USGS real-time reporting water level gauges within each of the leveed areas and support the USGS in developing field gauges that can survive severe storm events.** It is possible economic damages, human suffering, and loss of life would have been less if there had been gauges transmitting real time water levels to decision makers and the public. In addition, having actual water levels is important for analyzing the event itself, developing models for other events, and forecasting future flood levels.

3. **Develop a catastrophic event unwatering plan and conduct annual practices with local sponsors and other appropriate public agencies.** Minimizing the length of flooding in homes and businesses will reduce economic damages, human suffering, and loss of life. Closing storm-induced breaches, getting the permanent pump stations operational, and possibly creating deliberate breaches are difficult tasks. Having a coordinated and rehearsed plan ahead of time will reduce the length of flooding.

Post-IPET

With any study effort like IPET, there are usually tasks that the team would like to have completed to improve the results or to provide better information to the decision makers and public. Many of these additional tasks have come up during the modeling but could not actually be incorporated due to scheduling and model generation details. Below is a list of items for consideration by the team that will continue the interior drainage analysis using the models developed for IPET.

1. Calibrate the models with other historic events besides Hurricane Katrina and expand sensitivity test. This will be important when simulations are run with less overtopping. The interior drainage features and function will become more important in less catastrophic events.

2. Run the HEC-RAS models longer in time to cover the entire unwatering period for Hurricane Katrina to adequately respond to the IPET question, “What was the contribution of the pumping stations and drainage system in the unwatering of flooded areas?” Flood durations could then be estimated.

3. Convert the HEC-RAS models’ terrain and elevation data to the NAVD88 (2004.65) datum. This will make the results consistent with the other report volumes.

4. Develop HEC-HMS and HEC-RAS models for St. Charles East Bank and Orleans West Bank. Even though they did not flood severely in Katrina, their likelihood of flooding still needs to be evaluated for other storms and storm tracks.

5. There are many more simulations that could be run for the New Orleans area. Many were suggested during the IPET study, but they could not be run until after the model development is completed. Some of the scenarios suggested were:

    - Hurricane protection system as of 1 June 2006; Katrina storm
    - Hurricane protection system as of September 2007; Katrina storm
    - Hurricane protection system as of 1 June 2006; Other storms and tracks
    - Various levee and floodwall survivability; various pump station operation scenarios; various storms and tracks
    - Incorporate outfall canal closure structures and their impact on interior drainage.

6. Additional parts of the storm drain network can be added to the models if they are critical to the interior drainage analysis for one of the future simulations.

7. Evaluate and better understand the flow paths within basins.

8. Incorporate data that surfaced too late to be included in the models and continually update the models as the hurricane protection system is modified.

Pumping Station Performance

General

Historically, the pumping stations have not been considered to be part of the hurricane protection system except in a few instances where the buildings are a structural part of a levee or floodwall. Since much of the area is below the level of Lake Pontchartrain, sea level, and the Mississippi River, the pumping stations are needed to prevent flooding caused by accumulated rainfall and seepage, and (as in the case of Katrina) to evacuate floodwaters after a failure of the hurricane protection system. These stations would have performed as designed after Katrina to unwater their respective subbasins had the hurricane protection system not failed.

Only stations in Jefferson, Orleans, Plaquemines, St. Bernard and the east bank of St. Charles Parishes were investigated. This was because there was no significant flooding in St. Charles Parish and the west was not considered to be inside the hurricane protection system.

The flooding that resulted from the overtopping and failure of the levees in the Greater New Orleans area rendered many of the pumping stations inaccessible, inoperable, or without electrical power. None of the pump stations were designed in a manner to protect themselves from local flooding as happened during Hurricane Katrina. One third of the stations were significantly damaged by Katrina resulting in a 37 percent loss of capacity. Most of the pump stations require operators. Only a few have automatic controls that allow the station to operate without operators present. Some pumping stations were mechanically operational during the storm but were not available for service because the operators were directed to evacuate.

There are over 100 pumping stations in the five parishes. Some have been recently completed and others are approaching 100 years of age. Most of the pumping stations have significant variations in their design, construction, and capacity. Station designs range from large plants built of reinforced concrete to small capacity stations housed in metal frame buildings.

Operational power is provided by various means. Some stations use pumps directly connected to diesel engines. For many stations, power is normally provided by the electrical grid with backup diesel generators or direct drive diesel engines available when the electrical grid is out of service. Some of the older stations utilize 25 Hz power provided by a central generating plant to run the pumps. These stations use frequency changers to change 25 Hz power to 60 Hz power for the operation of their station service system. Some prime movers use gearboxes and a few use hydraulic motors and pumps to transmit the power from the motor or engine to the pump shaft.

Figure 7. Large horizontal shaft pump.

Many pumps – particularly the larger ones, have horizontal shafts with the impeller located above the normal water surface of the suction side. This type of pump requires priming the system by filling the pump waterway with water using an engine-driven vacuum pump. This process can take as long as 15 minutes per pump. To prevent backflow when the pump is shut down, a siphon discharge valve is placed at the highest point of the discharge pipe or a large valve or gate is installed in the discharge conduit. The siphon discharge pipe has the maximum elevation of its invert (i.e. the bottom of the conduit) located at an elevation slightly above the maximum water level on the discharge side of the pump. When the pump stops operation, the vacuum breaker valve opens admitting atmospheric air into the discharge pipe to break the siphon action and prevent reverse flow. However, if the water level on the discharge side is higher than the invert's high point, reverse flow will occur even with the vacuum breaker valve open. Reverse flow rates vary depending on the difference in water level on each side of the station and can be as great as twice the pump's rated discharge. "Trigger" points (i.e., the required water levels for reverse flow to commence) and reverse flow performance data on all pump stations are included in Appendix 7.

Katrina's storm surge resulted in water levels in Lake Pontchartrain that, for some pump stations, exceeded their design discharge water levels. This condition resulted in reverse flow through some of the unmanned pump stations in Jefferson Parish at a high rate of discharge[1], causing flooding in areas where the hurricane protection system did not fail. Reverse flow may have occurred at stations that were later flooded with waters from failed and/or overtopped levees, particularly in Orleans Parish. However, in these instances the volumes produced by backflow through the pumps were an insignificant factor (i.e. only contributed about 10% of the inflow in Jefferson Parish) in the flooding that occurred in those areas.

An example of how reverse flows occurred at the Suburban Pump Station in Jefferson Parish is shown in the Figure 8 below. In this case, the elevation of the invert's high point was exceeded by approximately 4 ft during Katrina and reverse flow occurred.

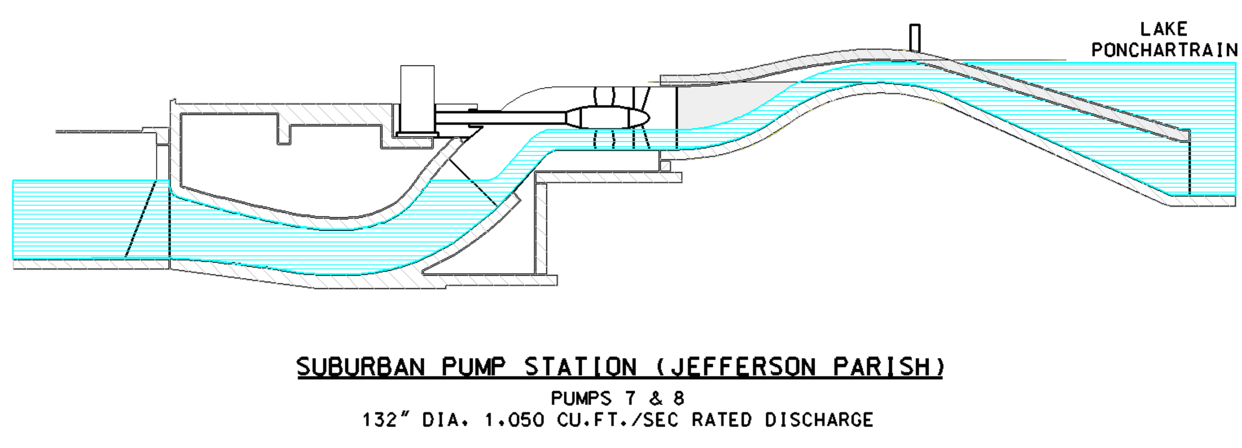

Figure 8. Graphic Representation of a pump showing reverse flow.

Due to the impacts of Hurricane Katrina, many of the pump stations were rendered inoperative. There are four reasons why pump stations failed to operate during the storm:

- **Evacuation**: Before the Katrina storm, all of the operators at the Jefferson Parish and St. Bernard pump stations were sent to safe havens away from their plants. During Katrina, plant operators at all but four stations in Plaquemines Parish also sought safe shelter. Only in Orleans Parish, operators stayed at their plants until the plants were no longer operable. During Katrina, only 16 percent, approximately 18,000 cfs, of the combined pumping capacity of Jefferson, Orleans, Plaquemines, and St. Bernard Parishes remained operational.

- **Flooding of station equipment:** This includes equipment that was flooded when the levees were overtopped or breeched and pumps that were turned off when it became apparent that they were merely circulating floodwaters through the breeches.

- **Loss of electrical service to the pumps:** Failure of both the primary and backup power supply systems.

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[1] Reverse flow discharge could be as high as twice rated discharge (in pumping direction) which is why it is "high."

- **Loss of lubricating and cooling water**: Some pumping stations rely on potable water from municipal water services for lubricating and cooling the pumps. Raw water from the canal or floodwaters is not clean enough to function as an effective substitute.

Pump Station List

I) Orleans Parish	**Rated Capacity (cfs)**	**Pumped During Katrina**	**Projected Capacity as of 1 June 2006 (percent)**
A) East Bank (E-3)			
1) OP 1 – PS 1	6825	No	92
2) OP 2 – PS 2	3150	No	100
3) OP 3 – PS 3	4260 *	No	100
4) OP 4 – PS 4	3720	No	100
5) OP 5 – PS 5	2260	No	56
6) OP 6 – PS 6	9480	No	89
7) OP 7 – PS 7	2690	No	100
8) OP 12 – PS 12	1000	No	100
9) OP 19 – PS 19	3650	Yes	71
10) OP I 10 – PS I 10	860	Yes	100
11) OP 17 – PS 17	625	No	100
12) Pric – Prichard	253	No	100
13) Mont – Monticello	99	No	100
B) East Bank (E-4a)			
1) OP 10 – PS 10 Citrus	1000	No	100
2) OP 14 – PS 14 Jahncke	1200	No	75
3) OP 16 – PS 16 St Charles	1000	Yes	100
4) OP 18 – PS 18 Maxent	60	No	0 (no power)
5) OP 20 – PS 20 Amid	500	No	50 (no power)
6) DR – Dwyer Rd	120	No	0 (under construction)
7) GS – Grant	192	No	91
8) Elai – Elaine St	90	No	0 (no power)
9) OP 15 – PS 15	750	No	100
C) West Bank (W-3b & W-4b)			
1) OP 13 – PS 13 (W-3b)	4650	No	100
2) OP 11 – PS 11 (W-4b)	1670	Yes	100
II) Jefferson Parish			
A) East Bank (E-2)			
1) PS 1 – Bonnabel	3750	No	100
2) PS 2 – Suburban	5440	No	100
3) PS 3 – Elmwood	5700	No	100
4) PS 4 – Duncan	4800	No	100
5) PS 5 – Parish Line	900	No	100
6) Canal Street	160	Yes	100
B) West Bank (W-1)			
1) LC1-PS – Lake Cataouatche 1	500	No	100
2) LC2-PS – Lake Cataouatche 2	600	No	100

3) BS-PS – Bayou Segnette	936	No	100
4) H90-PS – Highway 90	90		

C) West Bank (W-2)

5) A-PS – Ames	1930	No	100
6) W-PS – Westminster	1200	No	100
7) C2-PS – Cousins 2	2300	No	100
8) E2-PS – Estelle 2	1140	No	100
9) C1-PS – Cousins 1	960	No	100
10) Harv-PS – Harvey	960	Yes	100
11) W2-PS – Westwego 2	936	No	100
12) EST1 – Estelle 1	550	No	100
13) WEG1 –Westwego 1	300	Unk	100
14) MTKN – Mt Kennedy	274	Unk	100

D) West Bank (W-3)

15) Hero-PS – Hero	3902	No	100
16) P-PS – Planters	2360	No	100
17) Whitney-Barataria	3750	No	100

III) Plaquemines Parish

A) East Bank

1) Scarsdale	1780	No	100
2) Bellevue	516	No	79
3) Point A La Hache (East)	500	No	50
4) Belair	130	No	0
5) Braithwaite	109	No	100
6) Barriere	24	No	100

B) West Bank

1) BC-1 – Belle Chase 1	3500	Yes	60
2) BC-2 – Belle Chase 2	990	Yes	100
3) Lower Ollie (new)	300	Yes	100
4) Upper Ollie	250	Yes	100
5) Lower Ollie (old)	120	Yes	100
6) Point A La Hache (West)	50	No	68
7) Diamond	256	No	100
8) Hayes	500	No	100
9) Gainard Woods 1	408	No	100
10) Gainard Woods 2	568	No	100
11) Sunrise 1	200	No	0
12) Sunrise 2	290	No	100
13) Grand Liard (Buras)	840	No	100
14) Duvic (Venice)	560	No	100
15) Triumph	135*	No	Unk
16) Myrtle Point (Private)	1160	No	Unk
17) Pointe Celeste (Private)	992	No	Unk

IV) St. Bernard Parish

A) East Bank (E-5a)

1) F-1 – PS 1 Fortification	1245	No	100
2) M-4 – PS 4 Meraux	1245	No	100
3) JL-6 – PS 6 Jean Lafitte	1000	No	100
4) BD-7 – PS 7 Bayou Ducros	1017	No	100

5) SM-8 – PS 8 St. Mary	834	No	100
6) BV-3 – PS 3 Bayou Villere	500	No	0
7) G-2 – PS 2 Guichard	350	No	0
8) EJG-5 – PS 5 E.J. Gore	660	No	67
V) St. Charles Parish			
1) 4th Street	64	Unk	100
2) Bayou Trepagnier	800	Unk	100
3) Destrahan I (Ormond I)	756	Unk	100
4) Destrahan II (Ormond II)	931	Unk	100
5) Dianne	102	Unk	100
6) Engineer's Canal	124	Unk	100
7) Fairfield	25	Unk	100
8) New Sarpy	152	Unk	100
9) Oak Street	73	Unk	100
10) Oakland	67	Unk	100
11) Schexnaydre	208	Unk	100
12) Turtle Pond	42	Unk	100
13) Walker Canal	85	Unk	100

*Estimated – no nameplate

The pie-chart shown in Figure 9 indicates how the combined pumping capacities of Orleans, Jefferson, St. Bernard, and Plaquemines Parishes were affected by the storm. At some stations, more than one of the four failure types occurred. Only the circumstance that initially shut down each station is indicated. If a particular pump station was shut down due to flooding, and then later lost electricity, the lost capacity is only indicated to be due to flooding.

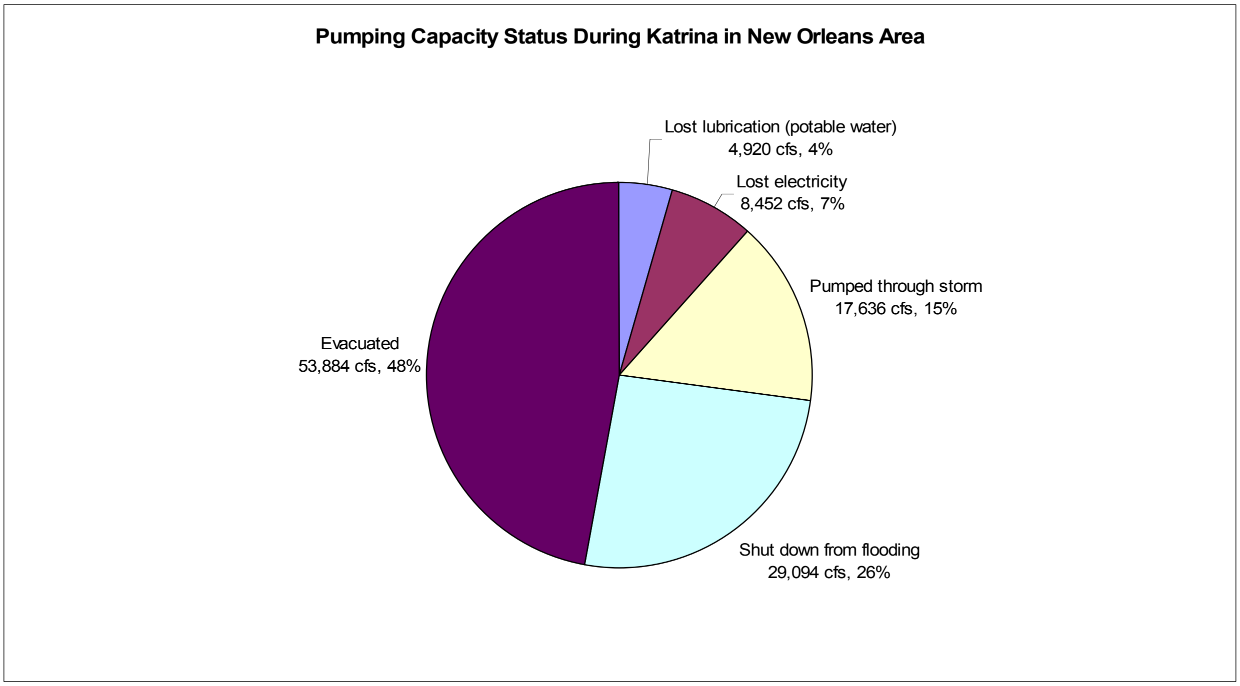

Figure 9. New Orleans area pump status during Hurricane Katrina (by rated capacity). Note: The cubic feet per second (cfs) of lost capacity indicated in the charts in this report are based upon the rated capacities of the pumps.

Appendix 7 of this volume contains summary and detailed information on the performance of the pumping stations by parish, station, and unit. It is organized in the following manner:

- General Summary
- Parish Map
- Drainage Basins
- Damage
- Improvements, recommended by Parish
- Station Description with Photos
- Station Operation during Katrina
- Pump Data
- Pump Operation Curves
- Pump Reverse Flow Curves
- Station Fuel Endurance.

The pump operational curves in Appendix 7 predict flow rates at various pool-to-pool heads. They are a combination of the pump discharge curve and system losses. This is explained in more detail in the appendix. Head loss due to accumulation of trash on the racks was accounted for. This loss was based upon the expectation that the racks would be relatively clean before a hurricane and that only stations with *climber* type trash rakes would be capable of operation during high winds (above 50 mph). Other types of raking systems typically require an operator outside during raking operations. See the appendix for more details.

Following is a summary evaluation of the pumping stations for each parish. For the purpose of this investigation, a total of 95 pumping stations were identified (see Pump Station List). Some stations have multiple buildings (such as Gainard Woods 1 and 2) and may be listed in other documents as a single station. Also, some larger stations have small continuous duty pumps whose capacities may not be included in the station's total capacity in various documents. Because of this, there may be small differences between the aggregate number of stations and parish pumping capacities as reported in the various PIRs and this report. A map of each parish showing the location of the pump stations investigated is presented. For each parish, except St. Charles, a bar chart is presented which shows the percentage of pump units available and operating between 28 August 2005 (the day before Katrina made landfall), and when evacuation of floodwaters ceased.

Jefferson Parish Pump Stations

Jefferson Parish has six pump stations on the East Bank and 21 on the West Bank. The 27 stations have a total rated capacity of 48,460 cfs to drain an area of 73,500 acres.

No Jefferson Parish pump station was flooded during Katrina and, as a result, none experienced significant damage. Primarily, the damage was to roofs, gutters, skylights, etc. The total estimated damage for all stations was $760,000. For their safety, the station operators were ordered to leave their stations (except for Harvey) prior to the arrival of Katrina. During Katrina, pumps were operated at only three stations. Harvey was operated by the station operators. Canal St. and Whitney-Barataria continued to pump unmanned. The surface water level in

Lake Pontchartrain exceeded the design level of the station discharges. This caused reverse flow to occur at the stations that discharge directly into the lake.

Figure 11 shows that 89 percent of the pump capacity in Jefferson Parish was unavailable due to crew evacuations. Refer to Appendix 7 for capacity data for the individual drainage basins in Jefferson Parish.

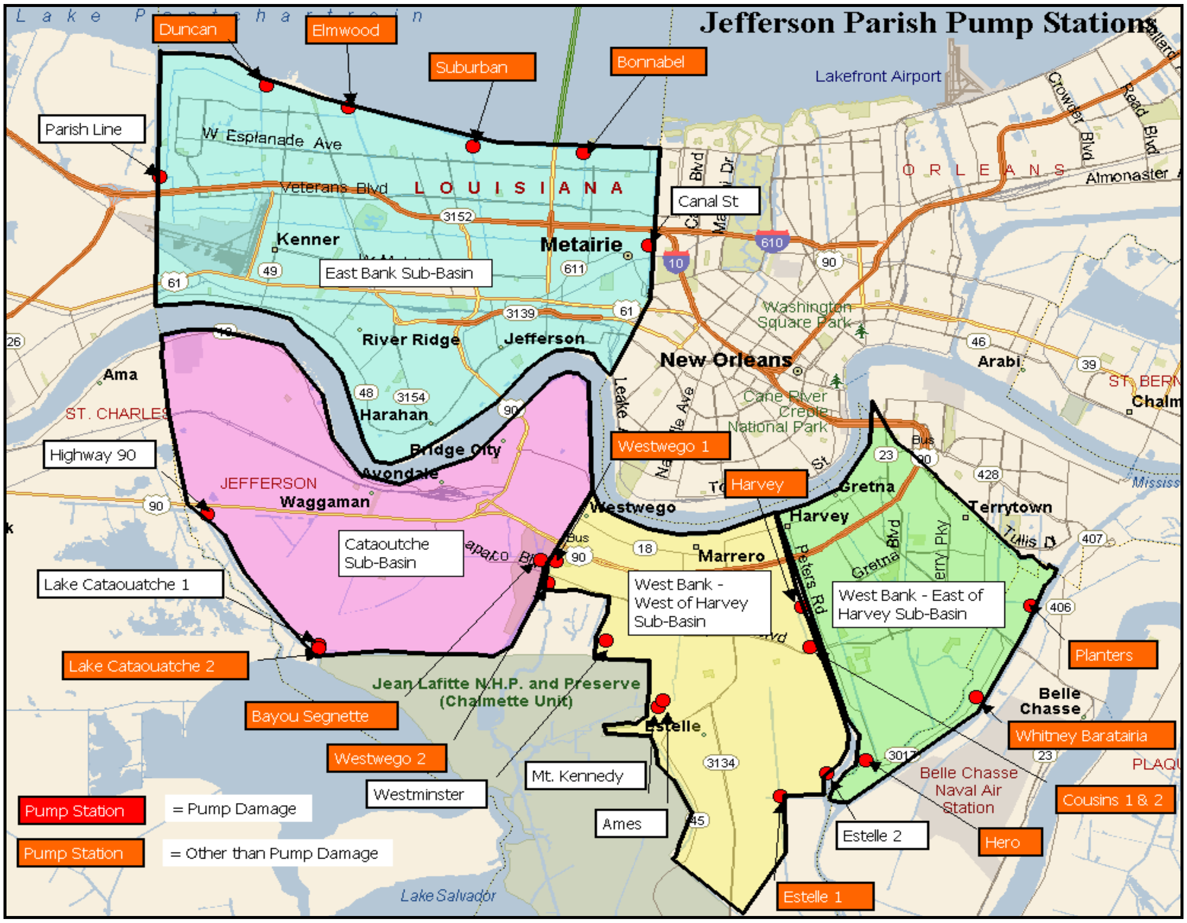

Figure 10. Jefferson Parish map of the pump stations and drainage areas.

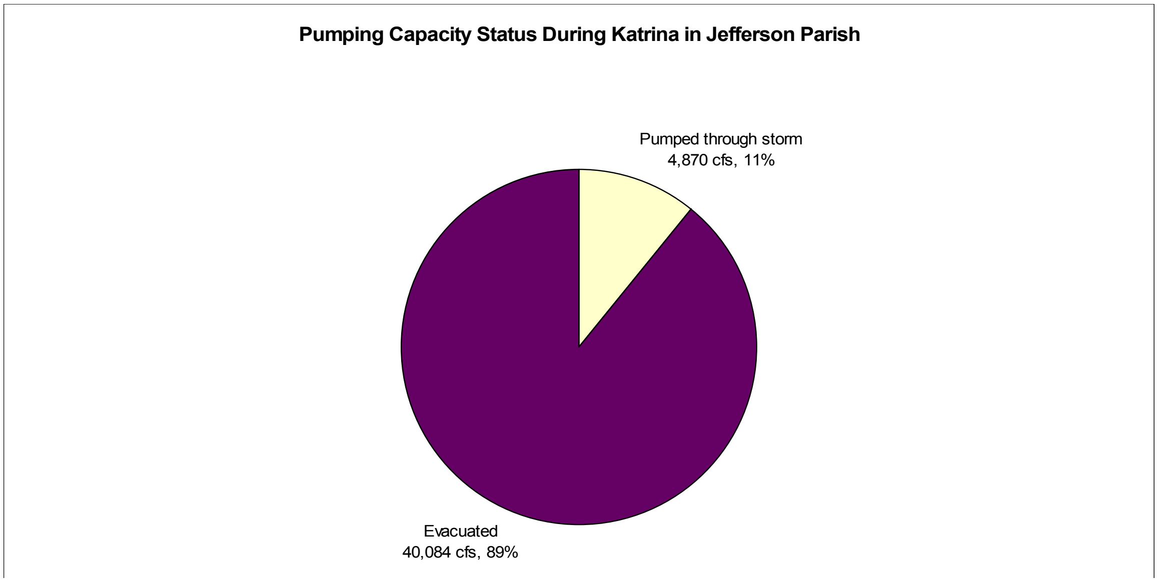

Figure 11. Jefferson Parish pump status during Hurricane Katrina (by rated capacity).

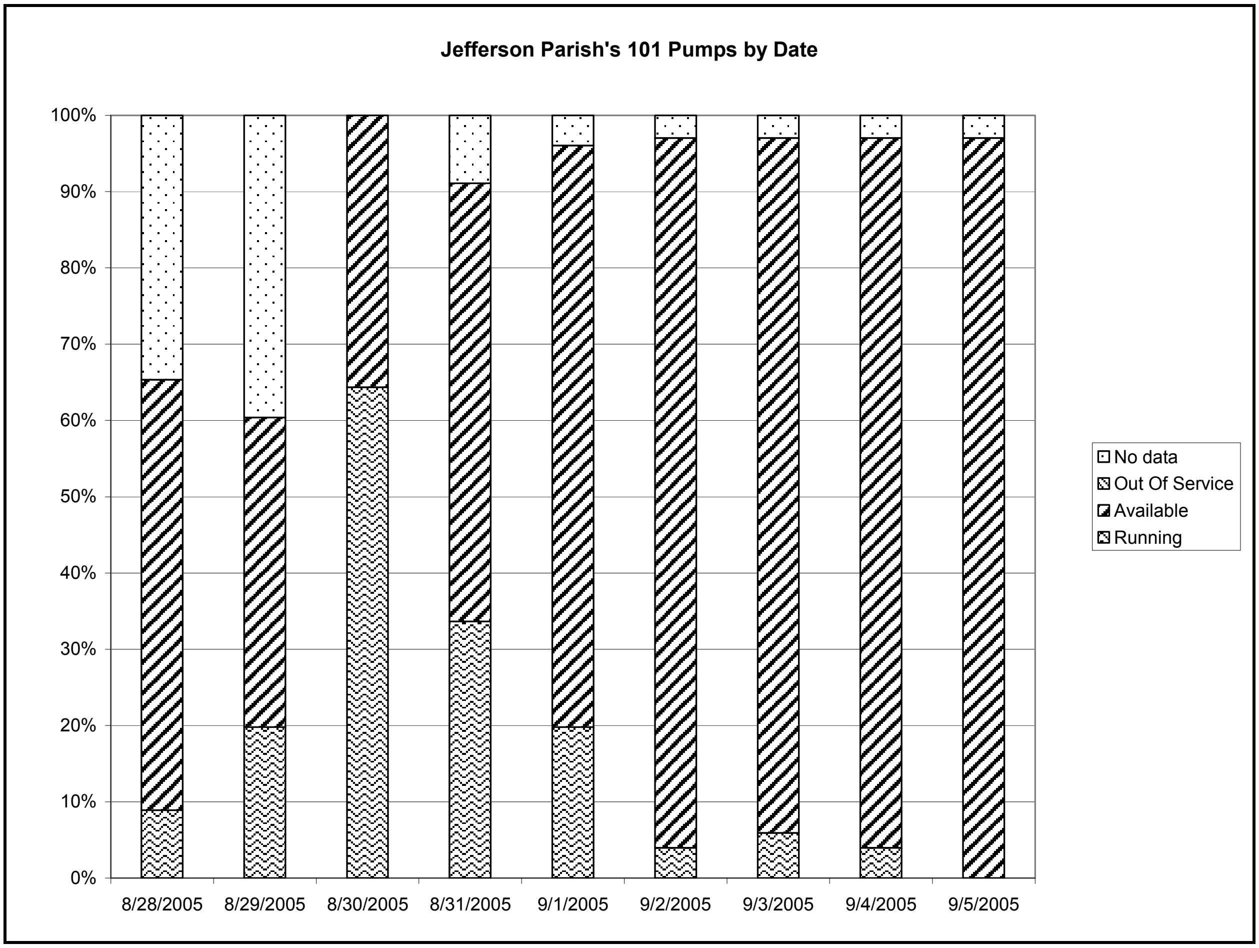

Figure 12. Status of the 101 pumps that were investigated in Jefferson Parish.

Since they suffered no significant damage during Katrina, the Jefferson Parish pumping stations are projected to be 100% operational by 1 June 2006.

Orleans Parish Pump Stations

Orleans Parish has 23 pump stations on the East Bank and two on the West Bank with a total pumping rated capacity of approximately 48,900 cfs to drain an area of nearly 60,000 acres. Twelve of the East Bank stations are located in the metropolitan area with the remaining ten located east of the IHNC (Orleans East). All stations in the metropolitan area have pumps which are electrically driven – most by direct-drive 25 Hz motors. A central diesel-electric generating station provides 25 Hz electricity for these stations. Additionally, there are two frequency converter facilities which convert 60 Hz electrical power from the local utility (Entergy) to 25 Hz. All stations in Orleans East and the two on the West Bank have pumps which are diesel driven.

The pump stations and generating station in Orleans' metropolitan area suffered significant damage – principally due to flooding of the electrical motors, diesel engines, generators and switchgear. Pump stations in the Orleans East area also were significantly damaged from flooding. Many of the Babbitt-lined pump bearings on the motor driven units were damaged from operating using dirty water in these water-lubricated bearings when the supply of city supplied water was interrupted. Some of the diesel engines were also destroyed. Neither of the two West Bank stations experienced any flooding. The Corps estimated a total damage of more than $39 million in its preliminary information report.

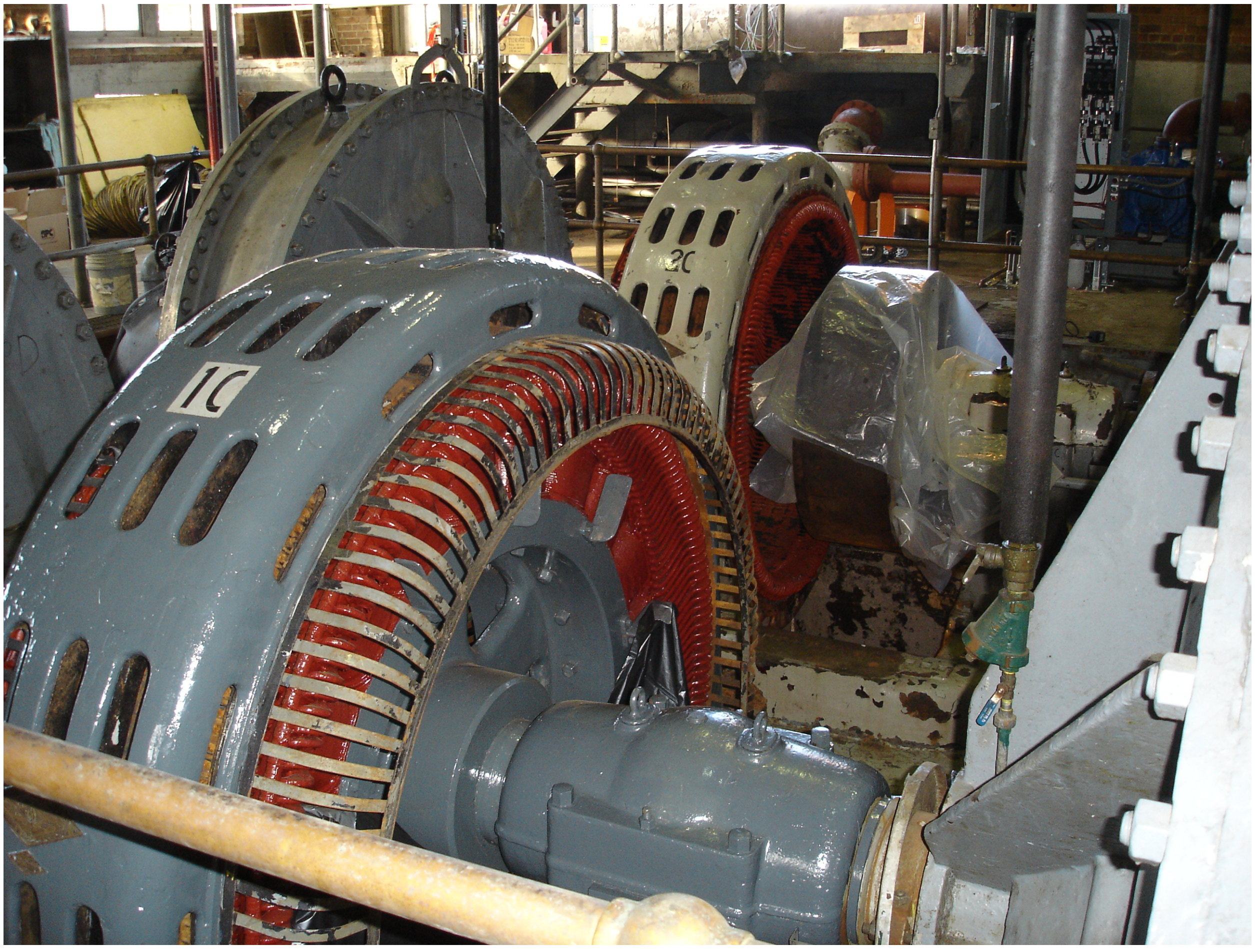

Figure 13. 25-Cycle electric motors directly connected to large horizontal pumps.

Prior to Katrina, the central 25 Hz generating station had 3 of the 4 steam-turbine generators operable. One was out of service due to control problems. Plant operators indicated it could have been put back into service if necessary. During Katrina, one generator was rendered inoperable due to wind damage to the building which induced damage to some switchgear. The remaining two operated until the morning of 31 August at which time the water supply to the steam turbines failed. Later, water entered the basement of the building causing damage to electrical equipment. This would have also shut down the water pumps.

Approximately half of the 25 pumping stations, including some of the major ones, received significant damage. All of the old 25 Hz electrical motors as well as the Carrollton frequency changer equipment that were submersed in water will need rewinding. Emergency repairs were made to the flood damaged windings by pressure washing them with fresh water and drying them out. This process cannot remove all the salt and other contaminants which accumulated in the cracks of the winding insulation which can leave a conductive path leading to a short circuit. At least one motor winding has already failed during testing. The tests performed are done at higher than operating voltage to assure a safety margin. If a motor winding passes the testing, there is no reason to expect its remaining life has been severely shortened.

At the other stations, some damage was sustained due to minor flooding or operation with dirty bearing lubricating water. When the supply of potable water was no longer available, dirty storm water was used to keep the pumps operational for as long as possible. Some stations sustained wind damage to roofs, doors, and windows.

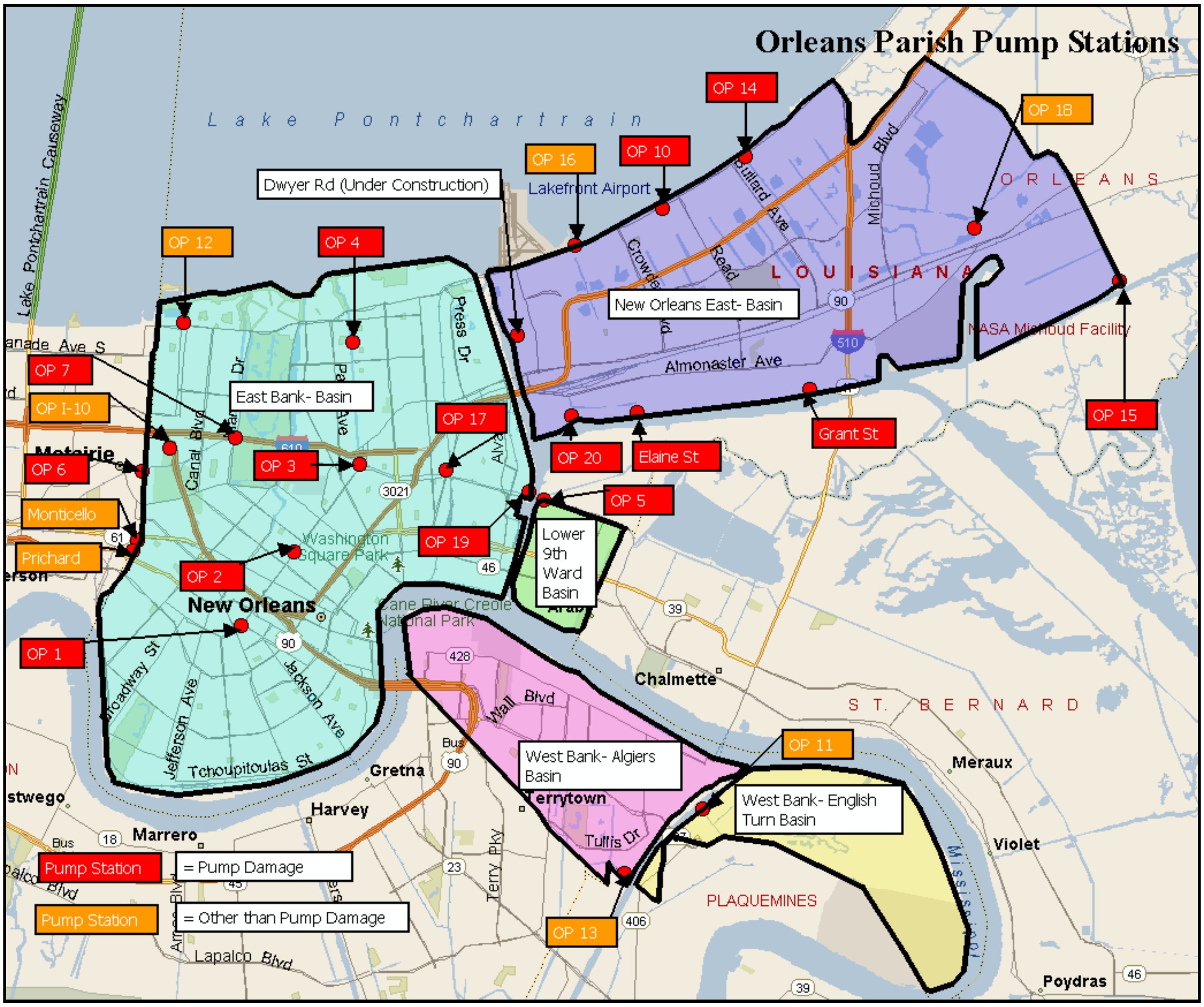

Figure 14. Orleans Parish Map of the pump stations and drainage areas.

Figure 15 gives a summary of the performance of all of the pumping stations in Orleans Parish. Fifty-eight percent of the total rated pumping capacity of the parish was lost due to flooding. Lost pumping capacity data vary significantly from basin to basin. Reference Appendix 7 for the specifics regarding lost capacities of the individual drainage basins.

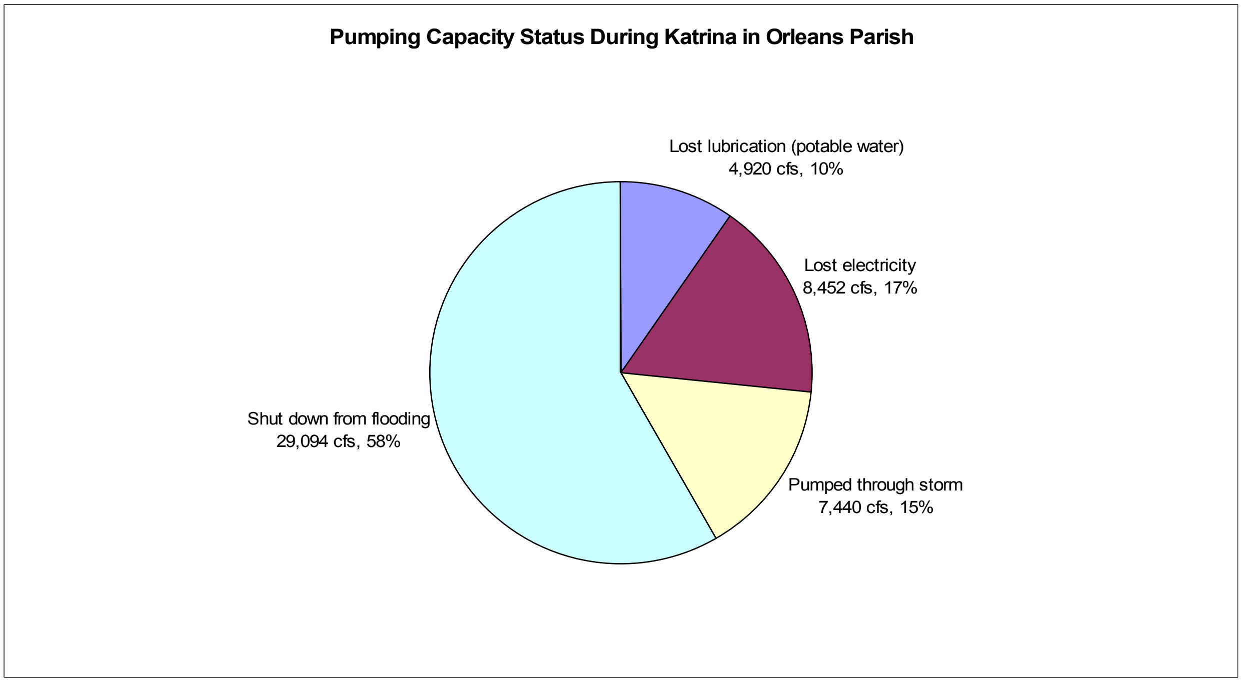

Figure 15. Orleans Parish pump status during Hurricane Katrina (by rated capacity).

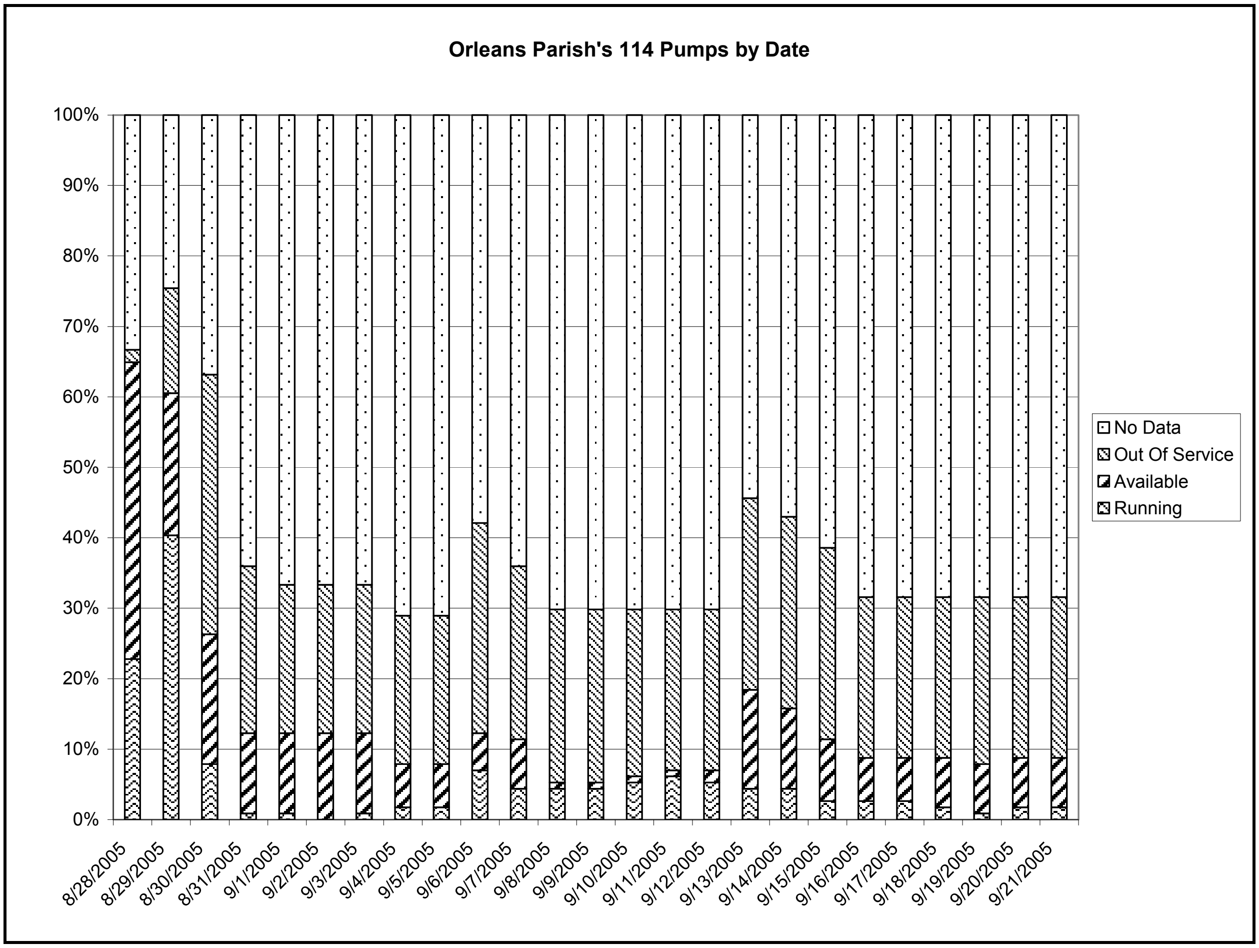

Figure 16. Status of the 114 pumps that were investigated in Orleans Parish.

Pumping capacities expected to be operational by 1 June 2006 are shown in the *Pump Station* List according to Task Force Guardian's 25 April 2006 report. Some stations will have slightly less due to the three motor failures which occurred on 26 April. The reliability of the pump motors that were subjected to inundation is very uncertain as evidenced by the failure of four pump motors after being washed and dried out. The temporary canal closure structures will also limit the useful pumping capacity at the stations that discharge into the canals during the time the needle gates are closed (i.e., when the level of Lake Pontchartrain increases during a hurricane).

Plaquemines Parish Pump Stations

There are 21 pump stations in Plaquemines Parish including two which are privately owned. These stations have a total discharge capacity of 12,065 cfs to evacuate accumulated precipitation in a drainage area of 55,000 acres. Most stations use pumps directly connected to diesel engines.

Nine stations suffered significant damage – principally from flooding. Total cost to restore the stations to pre-storm condition was estimated by Task Force Guardian to be $8 million. One station (Belair) was so damaged that a new pump house, including the foundation slab, is required. At stations where the diesel engines were destroyed due to flooding, new engines will be installed on an elevated platform or support which is now typical of newer construction. A hydraulic drive system will transmit power from the engine to the pump shaft.

Figure 18 shows that 57 percent of Plaquemines Parish's rated pump capacity was out of service due to crew evacuations. The remaining 43 percent of the rated capacity (at four plants) pumped through the storm. See Appendix 7 for the pumping capacity charts for the East and West Bank drainages.

Many of the pump stations were metal buildings and most suffered significant wind and water damage. At six stations, the water rose above the air intakes to the diesel engines which destroyed them. When new engines are installed, they will be raised up to a higher level to make a recurrence of damage due to flooding less likely. Task Force Guardian's Project Information Report dated January 2006 estimated total pump station damages to cost $8.2 million.

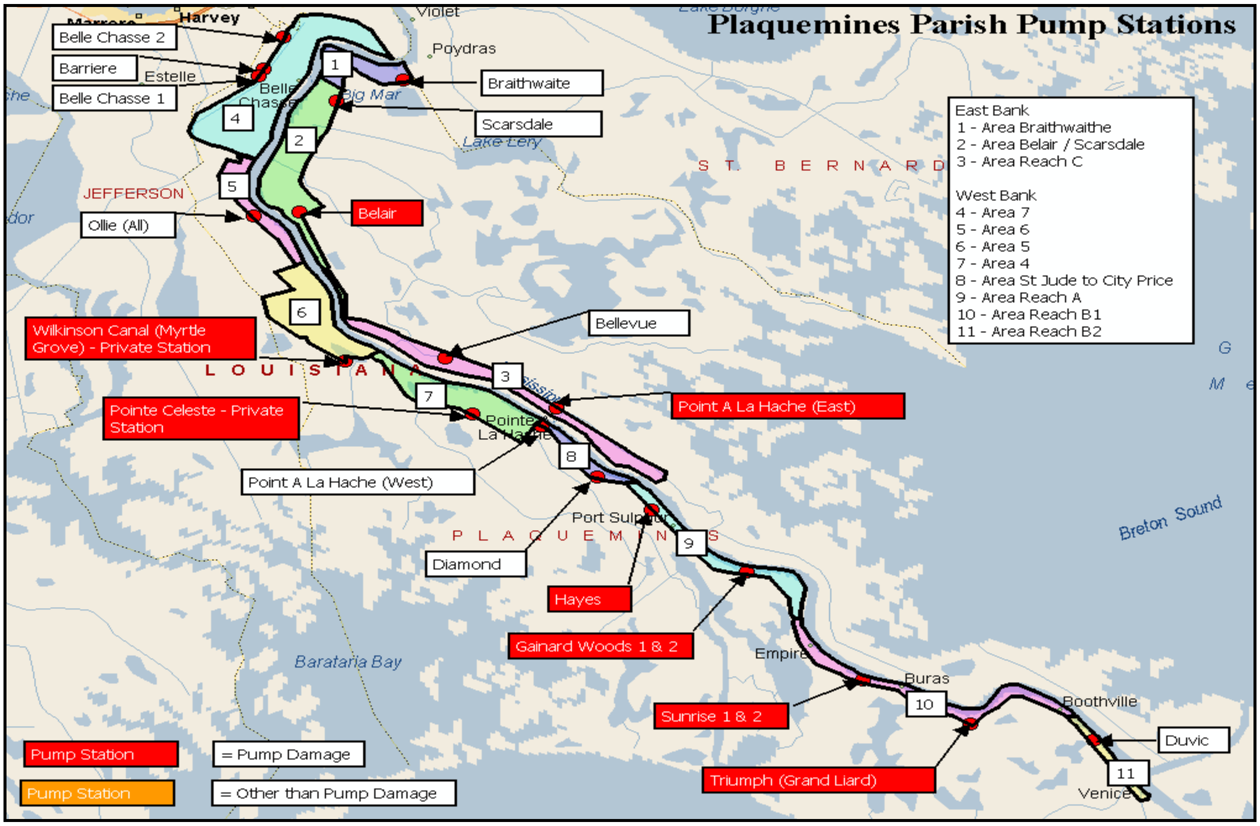

Figure 17. Plaquemines Parish map of the pump stations and drainage areas.

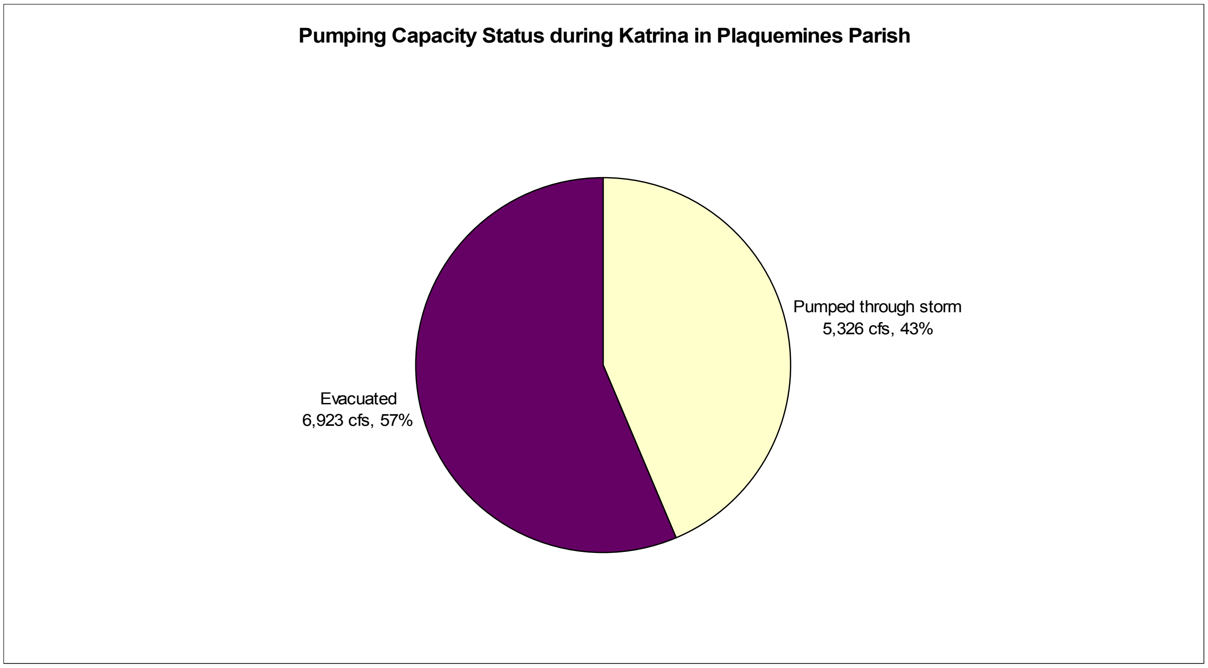

Figure 18. Plaquemines Parish pump status during Hurricane Katrina (by rated capacity).

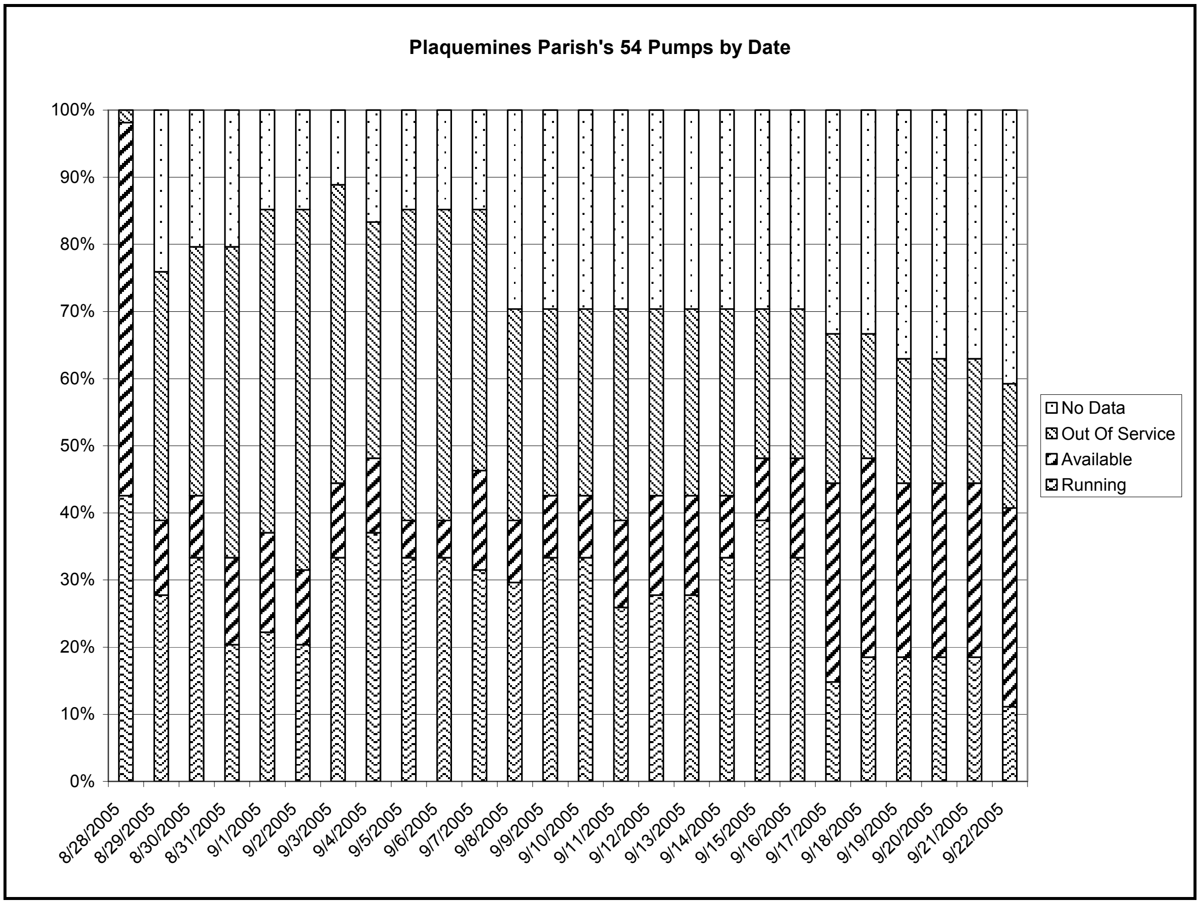

Figure 19. Status of the 54 pumps that were investigated in Plaquemines Parish.

St. Bernard Pump Stations

There are eight pump stations in St. Bernard Parish. Most pumps are powered by diesel engines. Five stations (representing 80% of total capacity) have operating floors approximately 12 ft above the natural ground surface which substantially reduced storm-induced damage. Three stations (pump stations 2, 3, and 5) were flooded to a depth of 6 to 8 ft above the operating floor which destroyed the diesel engines, vacuum pumps, and many accessories. Until this equipment can be replaced, the stations cannot be operated. The metal framed and sided buildings suffered considerable damage while structures built of concrete and brick experienced little damage. The three flooded stations accounted for 90 percent of the total estimated damage of $10.7 million according to Task Force Guardian's PIR.

The eight pump stations in St. Bernard Parish have a total discharge capacity of 7,000 cfs to evacuate accumulated precipitation in a drainage area of 17,620 acres. Most stations use pumps directly connected to diesel engines. Two use electric motors to drive the pumps.

Figure 20. Vertical diesel driven pump with right-angle drive speed reducer.

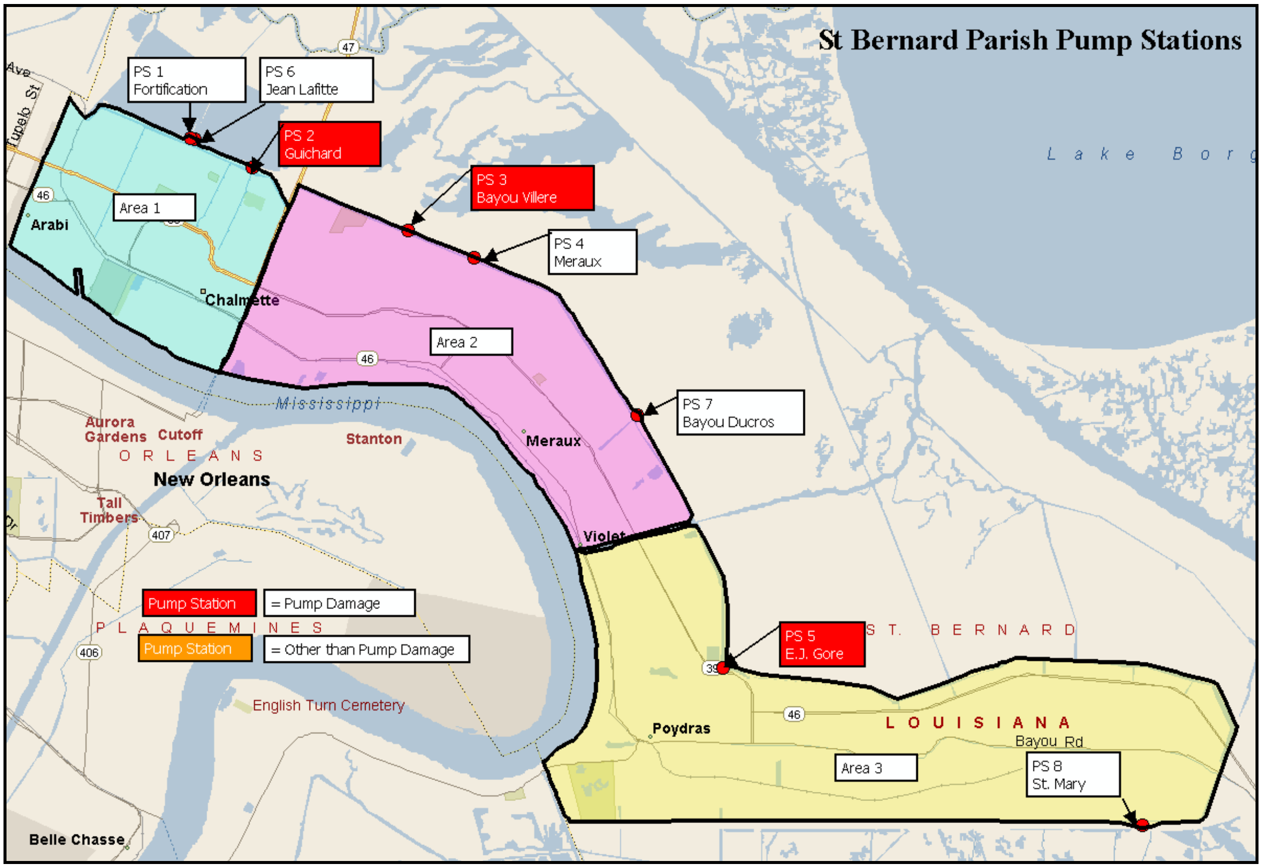

Figure 21. St. Bernard Parish map of the pump stations and drainage areas.

The pump stations in St. Bernard Parish did not operate during the storm due to evacuations prior to the arrival of the hurricane as shown in Figure 22 below.

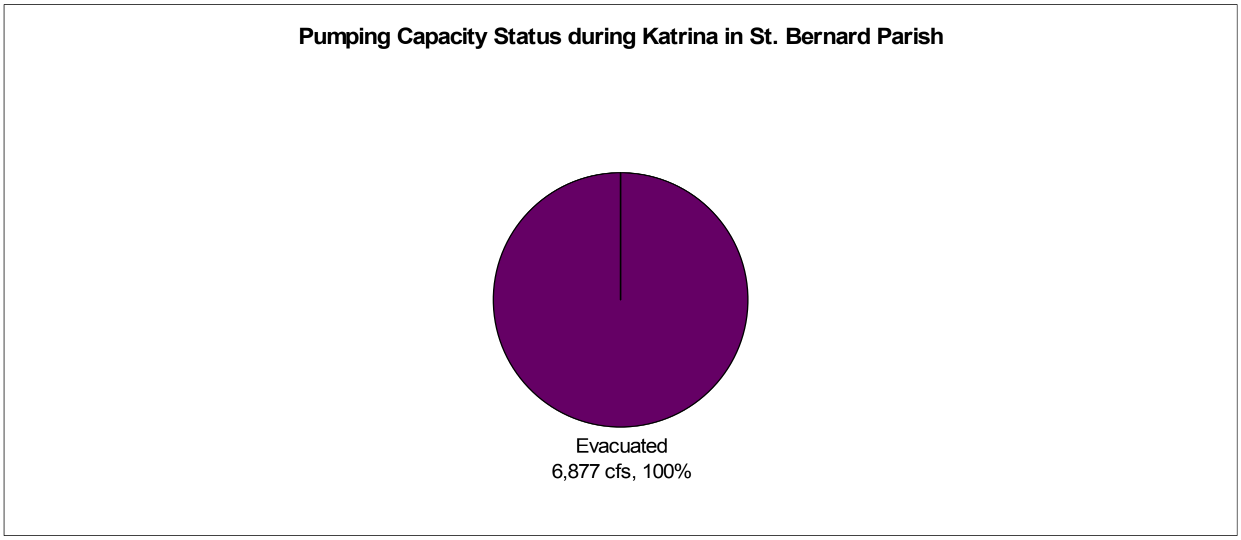

Figure 22. St. Bernard Parish pump status during Hurricane Katrina (by rated capacity).

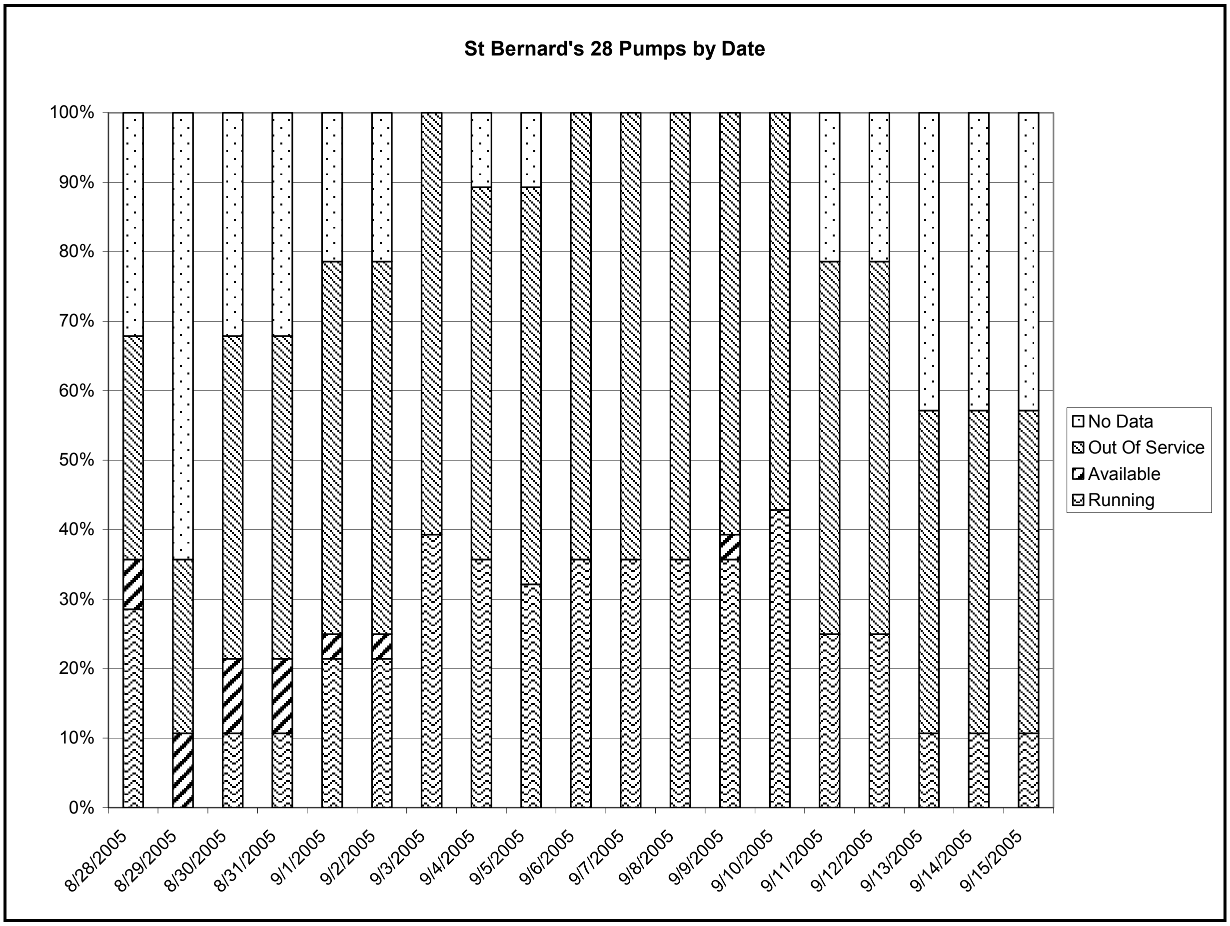

Figure 23. Daily status of the 28 pumps that were investigated in St. Bernard Parish.

Each pump station was visited to obtain operating logs of individual pump units. As can be seen in the performance chart, a significant amount of operating information was lost or not available. The chart shows the daily operational status of the percentage of 28 main pumps from 28 August, through 15 September when continued pumping was no longer required. Although only three of the eight stations suffered substantial damage, these three accounted for nearly half (13) of the pump units.

The projected operational status of the pumping stations as of 1 June 2006 is as follows:

Station PS1	100%
Station PS2	0
Station PS3	0
Station PS4	100%
Station PS5	67%
Station PS6	100%
Station PS7	100%
Station PS8	100%

Station PS2 and PS3 are only used in emergencies as they are older stations. Station PS5 had major damage and a portion of the station is still under repair.

St. Charles Pump Stations

There are thirteen pump stations in St. Charles Parish east bank. There was no report of significant damage to the pump stations caused by the storm. There were also no reports of major flooding in the Parish. The east bank stations (with the exception of Engineers Canal and Bayou Trepangier pump stations) pump into the open area inside the hurricane protection levee. The open area is drained naturally through four closure structures located on the hurricane protection levee. These structures contain gates that are closed when the lake reaches a predetermined level.

The thirteen pump stations in St. Charles Parish east bank have a total discharge capacity of 3,789 cfs to evacuate accumulated precipitation and seepage. The pump drivers consist of 10 electric motors and 19 diesel engines. Of the 19 diesel engines, 8 are natural gas and 6 have an electric motor as alternate driver.

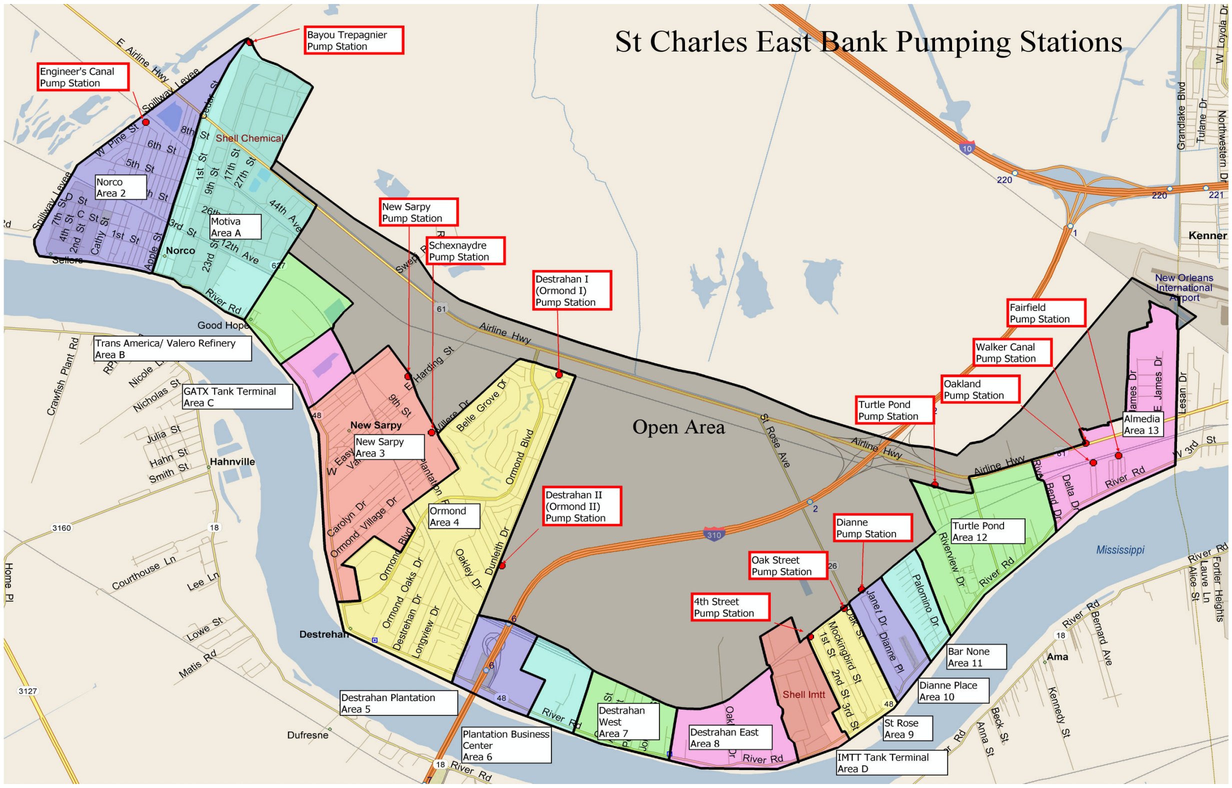

Figure 24. St Charles Parish map of the pump stations and drainage areas

Risk and Reliability

In anticipation of a hurricane, the local drainage entities pump down the drainage systems to their lowest levels to provide maximum storage for heavy rainfall. They are responsible to insure the readiness/availability of all their manpower and equipment. The continued operation at full capacity of all pumping stations is critical during hurricane events.

The extent of flooding in any particular area depends upon the rainfall associated with the storm coupled with the degree to which the levee and floodwalls may be overtopped. Overtopping depends upon the intensity of the storm, the track that the center or "eye" of the storm follows, and the speed at which it travels along the track.

Figure 25. Hydraulically driven submersible pump.

Minor to moderate flooding of the lowest lying areas may occur from rainfall alone, without any overtopping of the protection system. This type of flooding, although it may affect a large area and do great damage, will likely not damage the pumping stations and can thus be quickly removed by the pumps after the storm passes. At the point where the surge height reaches or exceeds the top of the levees and floodwalls, the protected areas will be completely inundated.

This will cause catastrophic damages including likely damage and shutdown of all pumping stations.

Even though an area is completely inundated and flooded during a hurricane event, if the levees or floodwalls are breached by the storm, areas above the level of Lake Ponchartrain will drain naturally with lower-lying areas remaining flooded after the event.

The continued operation of all pumping stations before, during, and after a hurricane is essential to prevent, control and eliminate flooding in the protected areas. An availability of 90 percent is a reasonable figure to use for modeling future system responses assuming the stations are not rendered inoperative due to being flooded or abandoned. This percentage has been often exceeded during hurricanes which have struck South Florida Water Management District's system, which is similar in size and complexity to New Orleans' pumping system.

At pump stations located along the hurricane protection levees and floodwalls, protection against high water levels resulting from hurricane storm surge is necessary. The stations themselves may be an integral part of the protection system, preventing storm surge levels from entering the building or grounds adjacent to the station. Where predicted storm surge elevations are sufficiently high, reverse flow may occur through the pump units. Appropriate measures must be taken to prevent reverse flow using physical barriers such as gates or operational procedures such as operations of pump units to prevent backflow.

The pumping stations are large and complex installations with a number of mechanical and electrical systems and subsystems which must act together with each other in order for the entire station to operate. Typically, the following systems are present:

- Pumps and intake/discharge piping
- Primary power supply
- Secondary/backup power supply
- Fuel storage and transfer
- Vacuum priming
- Vacuum breaker & air suppression systems
- Control systems and panels
- Air/water cooling
- Transformers

Emergency response actions for unwatering flooded areas must be coordinated as appropriate, with the following organizations or agencies:

- Emergency Operations Center (EOC), New Orleans District
- Parish governments, drainage districts, and emergency operations centers
- Municipal governments
- Public utilities

To assess the reliability of each pump station, elevations of critical components were used to determine loss of capacity resulting from various levels of flooding. The conditions of the equipment and pump station components were used to assess the susceptibility to hurricane events. The experience during Katrina was also used to assess the operational capability that would be anticipated as a result of hurricane activity.

Appendix 7 contains spreadsheets which identify critical pump station elevations (at which operation ceases), station fuel endurance data, prime mover data, and available backup energy sources.

Repairs to Pump Stations

Repairs to the pump stations are being managed by both the owning parish and by the Corps' Task Force Guardian. Urgently needed repairs for the winter storm season were managed by the parishes and paid for by FEMA. FEMA funded repairs principally in Orleans and Plaquemines Parishes. Other repairs to return the stations to pre-Katrina condition are being paid for and managed by the Corps. Not all repairs will be completed by 1 June 2006. In some cases (such for several stations in Plaquemines Parish), the repairs involved more than restoring the plant to its original design. At these plants with diesel engines at low elevations, new engines are being installed at higher elevations with hydraulic motors and pumps to transmit the power to the pumps.

Lessons Learned for Pumping Stations

While the pumping stations have not been considered as an integral part of the hurricane protection system, they should have been. Therefore, existing and new design criteria applied to the levees and floodwalls should also be applied to pumping stations.

Design, construction, operation and maintenance, of pump stations responsible for unwatering the various parishes should be under the control of a single entity. Currently these pump stations are controlled by the individual Parishes. This will improve the likelihood of more commonality of design, equipment, and spare parts, and more consistent maintenance practices and operator training.

A study should be initiated to consider replacement or rehabilitation of the 25 Hz electrical system in Orleans Parish to reduce operation and maintenance costs and improve reliability.

The following specific lessons learned fall into three categories. These are:

- Physical improvements to reduce the risk of the stations not performing their intended mission
- Physical improvements to reduce the cost of operations and maintenance to enable the parishes to maintain desired availability with diminished income due to fewer inhabitants than pre-Katrina levels
- Emergency response planning changes to address needs which are beyond the ability of the individual parishes to effect.

The following are lessons learned regarding the need for principal physical improvements to reduce the risk of station failures:

- Ensure the safety of operating personnel during a hurricane. Safe houses at or nearby the pump stations, reinforced control rooms within pump stations, or reinforcing the pump stations themselves to provide protection and creature comforts (such as food, water, rest areas, etc.) are needed. Remote controls will be needed for operators to continue to operate the equipment from these safe houses.
- Pump station structures should be able to withstand hurricane force winds without significant damage. Some stations are constructed of metal and/or have metal roofs which failed due to high winds. Modifications are needed to at least assure the stations can continue to be operated during peak hurricane force winds.
- Pump stations should not be allowed to permit reverse flow (backflow). Some stations which pump directly to Lake Pontchartrain (and possibly others which pump over levees) need to be able to prevent reverse flow from occurring. While the best solution for this would be to simply operate the pumps at all times when reverse flow is possible, there are several problems with this solution. These are:
    - The head may become so high as to overload the prime mover (diesel engine or electric motor)
    - There may be no water to pump
    - The pump unit may be undergoing maintenance and is disassembled or inoperable
    - The prime mover may stop or be stopped by lack of electrical power or diesel fuel, a mechanical failure, abandonment of the plant, etc.
- The communications systems between the parish command center, individual pump stations, generating station, other parishes and agencies, and those involved in emergency response, was poor to non-existent.
- Trash-raking equipment should remain effective during high wind conditions (i.e. when nobody can be outdoors). Specifically, plants which had caternary type rakes were least effective. The climber type rakes do not generally need an operator outside during operation while caternary type rakes do. Some plants which have intakes which are not affected by debris accumulation during hurricanes do not need such modifications.
- There should have been a backup system for the municipal water system at the New Orleans Sewerage and Water Board's central generating station for operating its steam turbines.
- A backup system for the municipal water system should have been provided at stations which use the source for lubricating pump bearings.
- Critical equipment should have been elevated or protected from water levels which occur during the design storm (i.e., the storm the levees and floodwalls were designed for).
- Plant 60 Hz power (for equipment other than pump prime movers) should have remained available when the local utility electrical supply system failed. Generally, this means some plants need small, engine driven generating sets to be installed which are designed for this purpose.

- At stations with electrically driven pumps (such as in Orleans Parish), the cooling and ventilation system should have been designed to enable operation with all windows and doors closed during high wind conditions. The heat from the motors was rejected to the air within the station causing excessively high temperatures.
- Stations with un-reinforced windows and rollup doors should have had shutters to protect the windows from hurricane force winds. Also, there was no bracing for existing rollup doors.
- After the storm, it took heroic efforts to re-fuel individual pump stations. There should have been an adequate fuel supply to feed the diesel engines until the station can be re-supplied via tanker truck. Air assets (helicopters) were unavailable for re-fueling as they were used for rescue operations.

The following are lessons learned regarding needed physical improvements to reduce the cost of operations and maintenance and to enable the parishes to maintain system availability with diminished income due to fewer inhabitants than pre-Katrina levels.

- Aging, high maintenance equipment is more expensive to maintain than newer, more reliable equipment. This may result in decreased availability in the future if revenue for operation and maintenance declines.
- Railroad underpasses for cars require pump stations for keeping them dry. This is a maintenance burden which would not exist if overpasses had originally been constructed.

The following are lessons learned regarding needed emergency response planning changes which are beyond the ability of the individual parishes to effect:

- It would have been wise to encourage parishes to have adequate supplies of fuel available at the stations during the hurricane season by eliminating the risk to pump station owners of having to dispose of large amounts of old, unusable fuel.
- Regional emergency access and communication needs went unmet during and immediately after Katrina.
- Even if there had been numerous safe houses at pump stations, the need to protect their families during Katrina probably would have been a reason for many operators to leave.