Polder Flood Simulations for Greater New Orleans

Hurricane Katrina August 2005

July 2007





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TU Delft

SVASEK HYDRAULICS

Preface

The objective of the project is to discern the contributions of various water inputs that combined led to the flooding of the three polders that comprise Greater New Orleans (GNO) during hurricane Katrina August 2005. State-of-the art computer models are used to assess these contributions. Like all computer models simulations, the output quality is dependent upon the input parameters and accuracy of the base grid. Our team has endeavored to use the best available data in this simulation.

The project team consists of M. Kok Ph.D. MSc. (project manager), B. Maaskant MSc, M. Aalberts BSc (all from the Delft University of Technology, Netherlands) and L. de Wit MSc (Svasek B.V., Netherlands). The project was independently reviewed by Professor J.K.Vrijling MSc (Delft University of Technology).

Delft July 30, 2007.

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1 Introduction

1.1 Hurricane Katrina

On the morning of August 29, 2005, Hurricane Katrina struck southeast Louisiana and triggered what would become one of the worst disasters ever to befall an American city. The storm overtopped levees and floodwalls throughout southeast Louisiana and also caused the levees and floodwalls in the New Orleans area to fail or breach in more than 50 locations. Water rushed into New Orleans and flooded over 80 percent of the city - more than ten feet deep in some neighborhoods [9].

Flooding of the city of New Orleans was caused by several sources (or causes): breaches, overtopping (of the levees and flood control structures) and rainfall. The question to be addressed in this report is to determine the relative contribution of the flooding sources for selected sites within each polder or bowl.

1.2 Objectives

The objectives of this research project include:

1. The use of computer models to generate flood simulations for the three polders or bowls (Orleans Metro bowl, New Orleans East bowl, and St Bernard bowl) that comprise the greater New Orleans area, utilizing the best available input data;
2. The assessment of the relative contribution of the main causes of flooding (breaches, overtopping, and rainfall) in the three polders utilizing water depth graphs (hydrographs) for selected locations.

1.3 General modelling approach

The flooding of New Orleans is simulated with the dedicated software package Sobek-1D2D [7]. Sobek-1D2D was developed by WL-Delft Hydraulics and is used worldwide in flood simulations. It has proved to be a reliable and stable program to simulate floods. It is the standard model used in the Netherlands for flood simulation [6]. Flooding is simulated with a combination of 1D (one-dimensional) and 2D (two-dimensional) elements; canals and boundaries are modeled as 1D elements and the flooding itself is modeled as a 2D process. Sobek-1D2D uses the robust numerical Delft Scheme to model the water motion (equations of Saint Venant) in the 1D and 2D elements. The results show detailed spatial information about water levels, velocities and rise rates over time and arrival times at desired locations.

The flooding of New Orleans is simulated in the three bowls (figure 1.1 - Orleans Metro bowl, New Orleans East bowl and St Bernard bowl) with three separate and independent model grids and simulations utilizing the Sobek1D2D computer flooding model.



Figure 1.1 The three bowls that comprise Greater New Orleans.

In general, the following approach was used. First, a grid data base model of the three polders was built. Two pumping stations in the Orleans Metro bowl are included in the model, because they were (partly) functioning during Katrina. Next, calculations with the three models were made using all sources of the flooding, and the results calibrated using available data of the flooding (mainly eye witness reports). The next step was the creation of 'what-if scenarios', for example what would have happened without the breaches, and so on. The following sources of the flooding are taken into account for the three bowls:

- Rainfall and pumping stations
- Overtopping of the levees and flood control structures
- Breaches of levees and/or floodwalls.

We have chosen to present the results at specific locations (sites). However, the model results are available for all sites. The impact of all scenarios was assessed with the Delft1D2D model, with one exception. The impact of the scenario "only rainfall and 100% pumps available" was assessed using a spreadsheet model, which includes rainfall and the capacities of the pumping stations. The Delft1D2D model is able to include the sewage system and the pumping stations, but this could not be accomplished within the deadline as indicated by counsel.

1.4 Definitions

The following definitions are used in this report:

Water level	Water height above or below NAVD88
Water depth	Water height or elevation above ground level
Rise rate	The height over which the water rises in one hour
Arrival time	Point in time where the first water arrives at a certain location
Overtopping	Water that flows over a levee or flood control structure due to an elevated water level which is higher than the crest level
Digital Elevation Model (DEM)	Model in which the considered area is divided in squares to which the elevation, with reference to NAVD88, is assigned
IPET	Interagency Performance Evaluation Task Force
NOAA	National Oceanic & Atmospheric Administration
ILIT	Independent Levee Investigation Team
Grid	Computational layer in which the considered area is divided in squares, for each square the water motion is calculated
Polder or bowl	An area that is below sea level and is enclosed by an uninterrupted chain of water retaining structures, levees and/or high grounds
MRGO	Mississippi River Gulf Outlet
IHNC	Inner Harbor Navigation Canal
GIWW	Gulf Intracoastal Water Way
NAVD88	NAVD88 2004.65

2 Input data and Model setup

2.1 Assumptions

In the simulation of Katrina flooding of New Orleans the most important processes of the flooding are incorporated. Some assumptions however remained unavoidable. The assumptions used in the simulation are:

- Overtopping by waves is not taken into account directly, but when erosion occurred due to wave overtopping this is taken into account in the crest elevation. The water volume from wave overtopping is small compared with the overflow volume from overtopping when the still water level is higher than the crest level.
- Sewers, ditches and other small waterways are not represented in the model. These waterways may have resulted in faster initial spreading of the water, but have negligible influence on the final water levels inside the three bowls.
- Buildings and other structures are not incorporated. They may have blocked water flow and changed flow directions. This influence is local, the overall influence of buildings and structures is taken into account in the bottom roughness (friction to flow) used in the model.
- No distinction is made between house blocks and streets in the elevation and roughness used in the model. The results show a general picture. At locations of houses flow velocities will be overestimated; at locations of streets the velocities will be underestimated.
- The interaction between surface water and groundwater is neglected. It is assumed that the soil is fully saturated, which seems to be a good assumption for the situation just before Katrina.
- The direct impact of wind is not taken into account.
- Under seepage below or through levees or flood control structures is not taken into account. All evidence is that under seepage volumes are negligible in comparison to the final water volumes within each bowl.

2.2 Data

All input data such as topography, surge hydrographs, rainfall, levee and floodwall crest heights, size and depth of breaches, levee breach times and pump station operation was acquired from US experts. The interior bowl or flood model was built on these data. The project team has, as far as possible, reviewed whether the data is consistent with other available data in the various reports of IPET, Team Louisiana and ILIT (see reference list). We know that there are uncertainties in the data, but we used, according to our knowledge, the best available data.

Data used in the flood simulation:

- Digital elevation model (DEM) available for the whole area with 15ft resolution, the resolution around levee crests is one feet, as supplied by Mr. Chad Morris, a professional surveyor.
- Surge hydrographs (graphs of water level variation over time due to hurricane Katrina) were obtained for ten pertinent locations adjacent to the polders from Dr Paul Kemp, a storm surge expert and oceanographer. See figure 2.1 for the locations and table 2.1 for the period covered by the time series.
- Information on the breach locations and sizes was obtained from Geographical Information System (GIS) data delivered by Mr. Chad Morris. Timelines for the breaches were obtained from the Team Louisiana Report [3].
- Time series of rainfall are delivered by Dr. Lee E. Branscome (CCM, Climatological Consulting Corporation) for the six areas numbered 1 to 6 in figure 2.2. For the three bowls three different time series are used as input in the model. The time series of Orleans Metro is equal to time series one, the time series of New Orleans East consists of the (area) weighted average of time series two and three and the time series of St. Bernard consists of the (area) weighted average of time series four, five and six.
- Eye witness reports from the IPET and Team Louisiana reports.

In the following sections the input data on the breaches for the three bowls will be discussed in detail.



Figure 2.1 Locations of available surge hydrographs used in this modeling study.

Table 2.1 Start and end point in time for the surge hydrographs.

	Location	Start	End
a	17th Street Canal	2005-08-25 07:30	2005-08-30 05:00[1]
b	London Avenue Canal	2005-08-25 07:30	2005-08-30 05:00[1]
c	Airport	2005-08-25 07:30	2005-08-30 05:00[1]
d	IHNC	2005-08-25 07:30	2005-08-30 13:00[1]
e	IHNC near lock	2005-08-25 07:30	2005-08-30 05:00[1]
f	GIWW B. Sauvage	2005-08-25 07:30	2005-08-30 13:00[1]
g	GIWW Paris Road	2005-08-25 07:30	2005-08-30 13:00[1]
h	MRGO B. Bienvenue	2005-08-25 07:30	2005-08-30 13:00[1]
i	MRGO B. Dupre	2005-08-25 07:30	2005-08-30 13:00[1]
j	MRGO Shell Beach	2005-08-25 07:30	2005-08-30 13:00[1]



Figure 2.2 The six subdivisions of greater New Orleans as used to input rainfall data.

2.3 General Model setup

The Sobek-1D2D numerical model we used operates on the metric system of measurement. We then convert this data to the imperial system for purposes of this report. Because there is no interaction between the three bowls St. Bernard, New Orleans Central and New Orleans East, they are modeled separately.

[1] The surge level at 09-03-2005 0:00 is 2.5 ft (0.762 m). All simulations end before this enddate. Simulations between the end of the surge hydrograph data and the enddate were linearly interpolated.

Grid
The two dimensional (2D) area in the model consists of a grid with computational cells with 50m (164 ft) sides. In this way each bowl consists of approximately 80,000 cells. The elevation of each cell is based on the DEM data. Levee crest the heights, given the sometimes marked variations over short distances, are carefully inserted into the model. Sobek-1D2D calculates the water levels and velocities in every grid cell.

Simulation period
All simulations start at 28th August 2005 0:00am and continue for at least two days. There are no simulations after 2nd September 2005 12:00pm.

Overtopping
Around every polder the water bodies are modeled using the available surge hydrographs as presented in figure 2.3. As soon as the water level gets higher than the crest height of a part of the levee or flood control structure, overtopping begins and water flows into the polder. At breaches a gap in the levee or flood control structure is modeled.

Rainfall
The time series used for rainfall are shown in figure 2.4. The model assumes that the rainfall occurs uniformly over each subsection (figure 2.2).

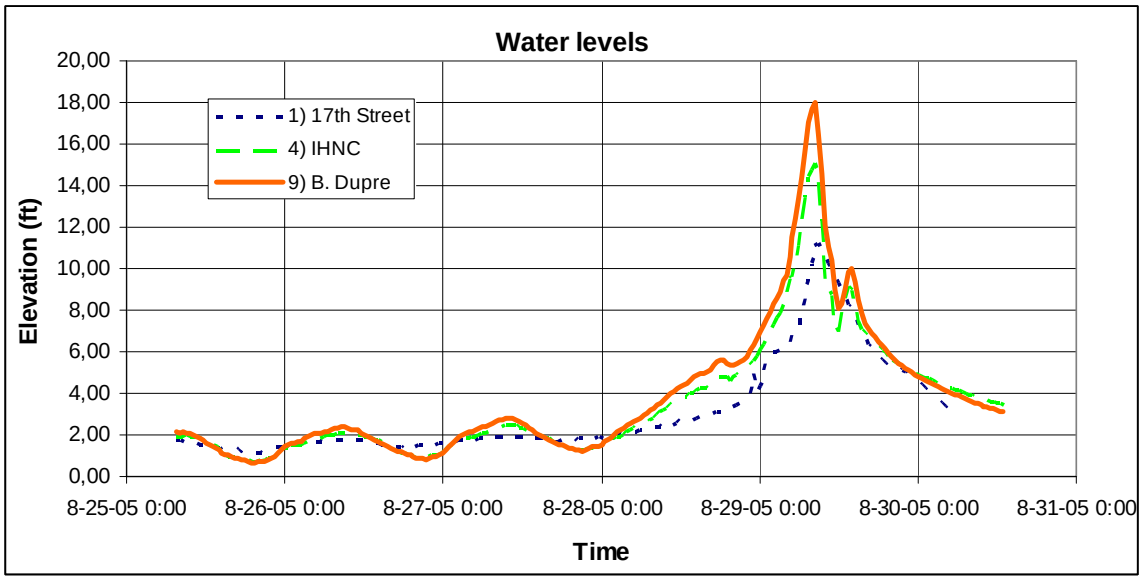


Figure 2.3 Surge hydrographs for 17th street, IHNC and B. Dupre

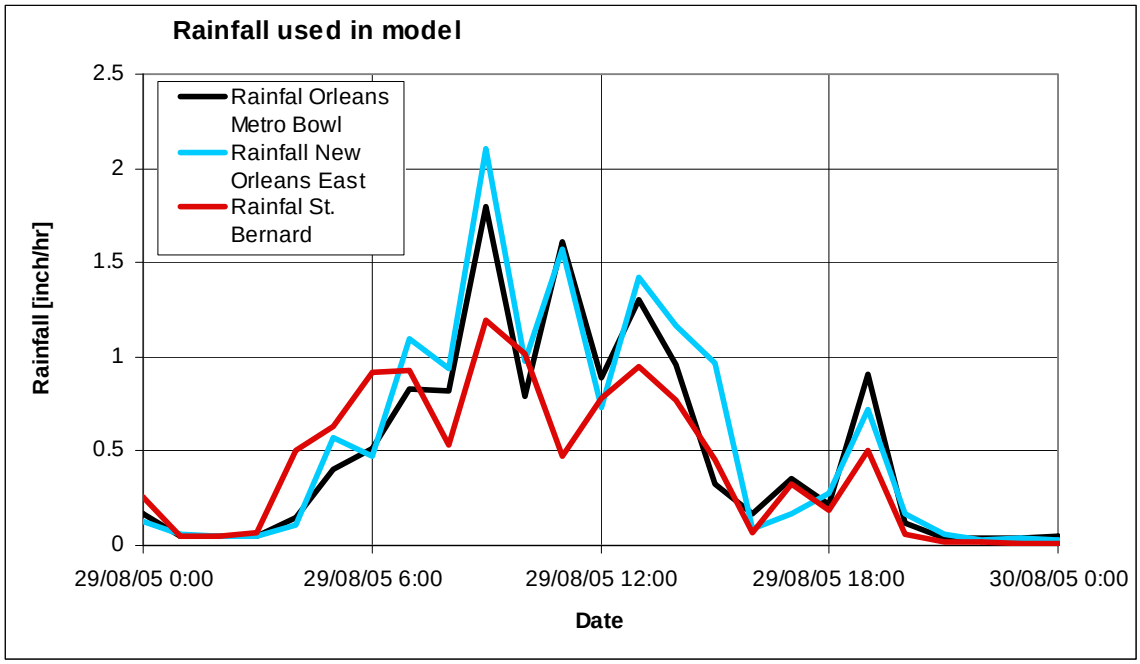


Figure 2.4 Rainfall time series used in model

3 Orleans Metro

3.1 Calibration of the model

Figure 3.1 shows the Digital Elevation model (DEM) of the Orleans Metro bowl. The arrows and numbers in squares correspond to the breaches given in table 3.1 and the arrows and numbers in circles correspond to the pumps which where available during Katrina (table 3.2). These breaches and pumps in combination with the rainfall and water levels as presented in section 2.3 are the basis of the model for the Orleans Metro bowl.

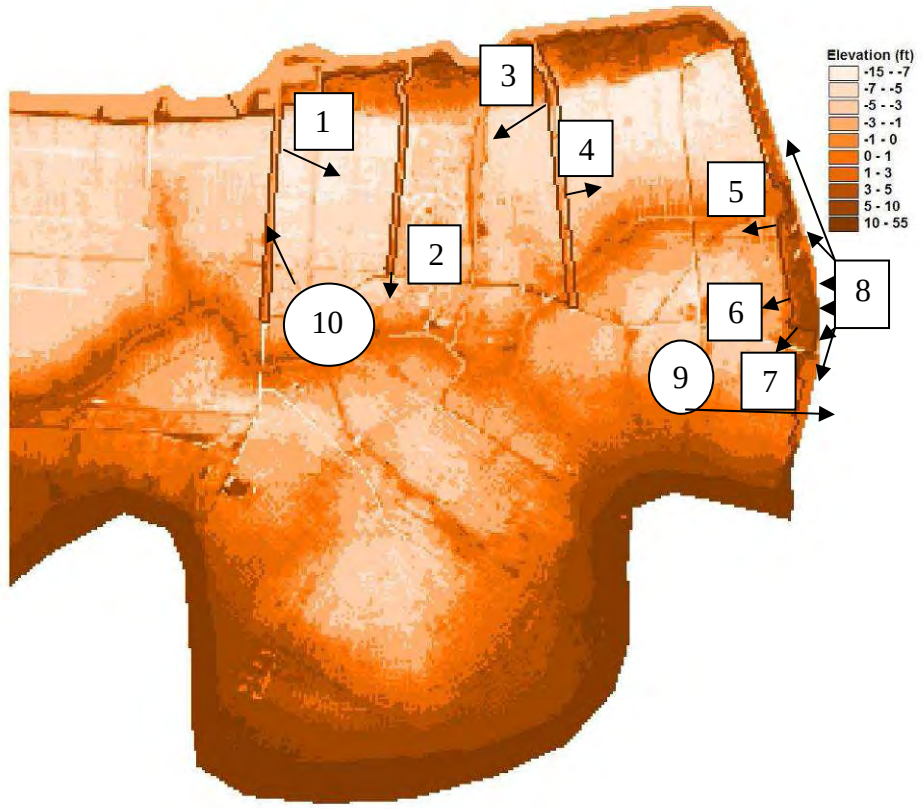


Figure 3.1 DEM Orleans Metro bowl, including breach locations (numbered squares) and pump stations (numbered circles). Note how this polder actually consists of several small bowls separated by natural ridges and/or railway or road embankments.

Table 3.1: Information on the Breaches in Orleans Metro bowl

Nr.	Description	Width	Elevation height	Time breach development
1	17th street	458 ft (139.6 m)[1]	Sill elevation -3.0 ft (-0.91 m)[1]	6:00 - 7:00[2] Major breach at 9:00[3]
2	Orleans canal	300 ft (91.4 m) 70 ft (21.3 m)	Sill elevation +9.5 ft (+2.90 m) Sill elevation +9.1 ft (+2.77 m)	7:30 - 8:00
3	London West	400 ft (121.9 m)[1]	Sill elevation -3.5 ft (- 1.07 m)[1]	7:00 - 9:00[4]
4	London East	231 ft (70.4 m)[1]	Sill elevation -20.0 ft (-6.10 m)[1]	7:00 - 9:00[3]
5	Railroad	37 ft (11.3 m)[2]	Sill elevation +5.0 ft (+1.55 m)[2]	4:30 - 5:00[2]
6	IHNC West floodwall	148 ft (45.1 m)[1]	Sill elevation +1.0 ft (+0.30 m)[1]	7:00 - 8:00[2]
7	IHNC West levee	200 ft (61.0 m)[1]	Sill elevation +1.0 ft (+0.30 m)[1]	5:00 - 6:00[5]
8	Overtopping from IHNC	Over a length of approximately 12000 ft. Position and width based on GIS data[1]	Differences in sections, based on GIS data[1]	7:00 - 7:30[6]

Table 3.2: Information on the pumping stations in Orleans Metro bowl[7]

Nr.	A) East Bank (E-3)	Rated Capacity (cfs)	Capacity (m^3/s)	Pumped During Katrina?	Projected Capacity as of 1 June '06
9	3) OP 19 – PS 19	3650	103.4	YES	71%
10	10) OP I 10 – PS I 10	860	24.4	YES	100%

[1] Source: GIS data with positions, widths and sill elevation heights of the breaches [delivered by Chad Morris 28-6-2007]
[2] Source: Team Louisiana report table 3, page 54 [4].
[3] Source: IPET volume IV: The Storm, page 169 [1].
[4] Source: IPET volume V: The Performance Levees and Floodwalls, page 40 [2]
[5] Source: IPET volume V: The Performance Levees and Floodwalls, page 53 [2]
[6] Source: Independent Levee Investigation Team (ILIT), page 7-6 [5]
[7] Source: IPET volume VI: Performance Interior Drainage and Pumping, page 31 [3]

Calibration results

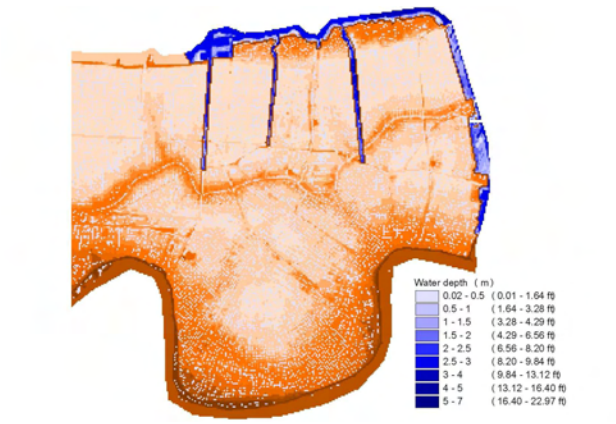
Figure 3.2 shows the progress of the simulated flood for the Orleans Metro bowl over time. The first figure is a snapshot August 29th at 5:00am; it shows only minor rainfall and a small breach in the IHNC at the location where the railroad crosses the levee. In the next hour the breach at the 17th street starts. This is consistent with the IPET, Team Louisiana and the ILIT reports.
The water levels near the 17th street breach were lowered because of blocking debris at the entrance of the 17th street canal.

According to IPET [1, page 181] site 11 started to flood at 09:00 - 10:30am, and the results of this flood simulation model do confirm this IPET observation.

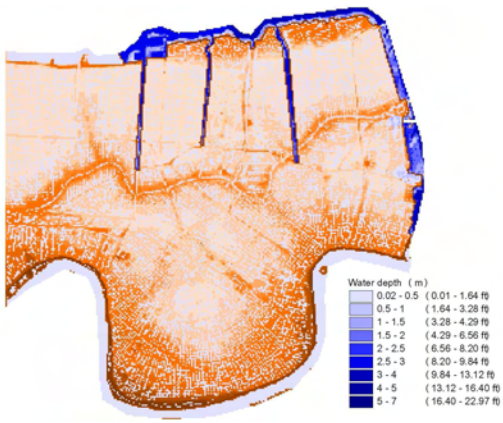
An eyewitness [1, page169] near the 17th Street Canal breach heard loud noises at 09:00am. Other eyewitness reports suggest that the breach occurred between 9:10am and 9:25am, so for the model we assume a 9:00am breach.

IPET reports [1, page 171] that no flooding was observed at site 14 until about 12:30pm on Monday afternoon. Our flood simulation model suggests that flooding started at approximately 12:00pm. This variance is within the 'error band' of eyewitness reports who would have been dealing with rain and poor visibility, wind, and the general distraction of the noise and circumstances of a hurricane passing overhead.

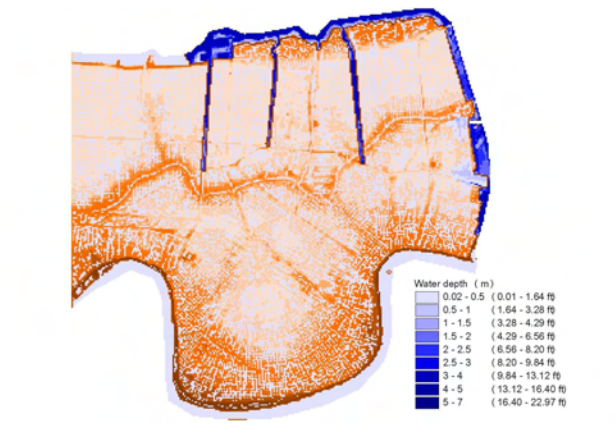
Site 19 starts flooding after 1:00pm, where eyewitness reports in IPET [1, page 173] state that the flood started at 1:00pm at this location. Again this variance is within the 'error band' of eyewitness reports who would have been dealing with rain and poor visibility, wind, and the general distraction of the noise and circumstances of a hurricane passing overhead. Thus we feel there are really only minor differences between eyewitnesses and the model results, which adds to our confidence in the results of the model.



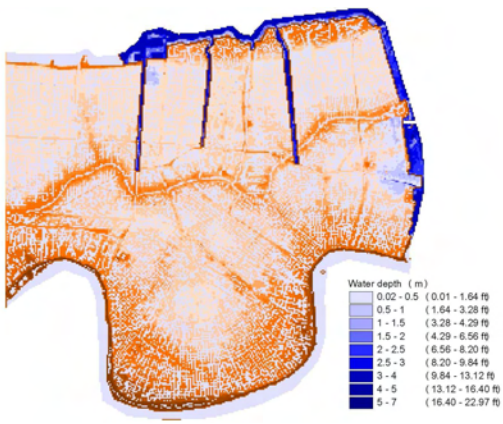
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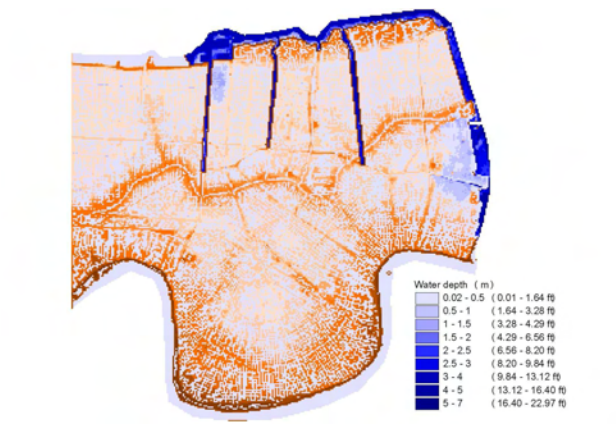
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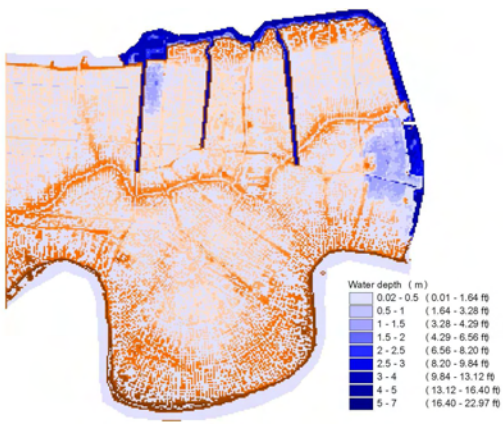
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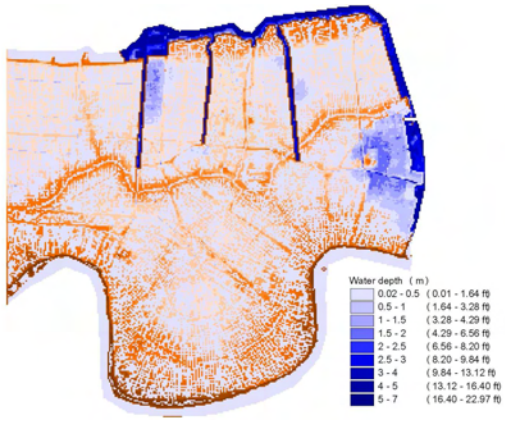
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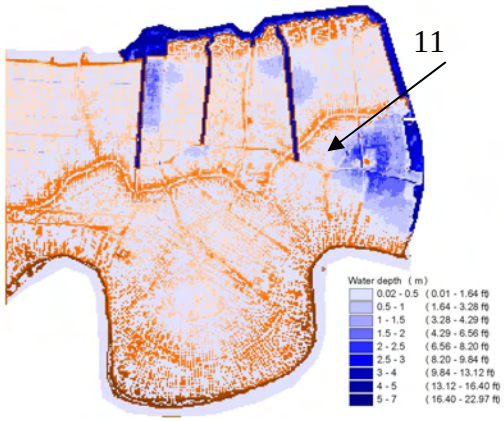
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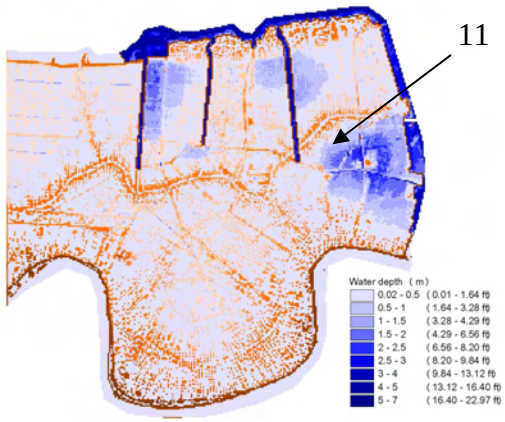
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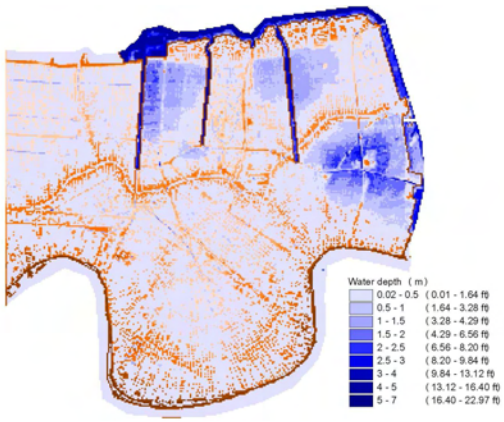
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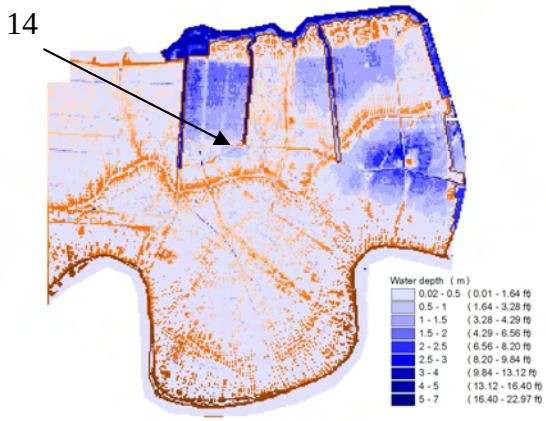
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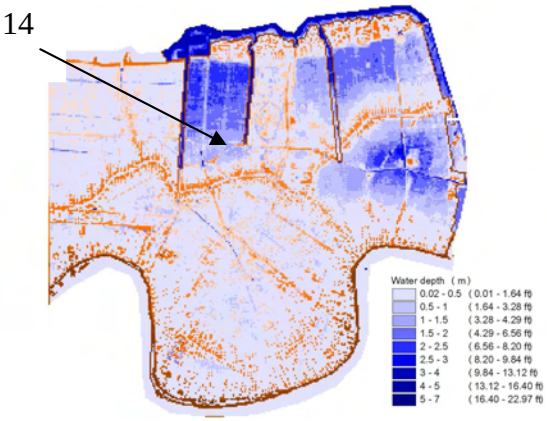
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12.00 h 2005-08-29

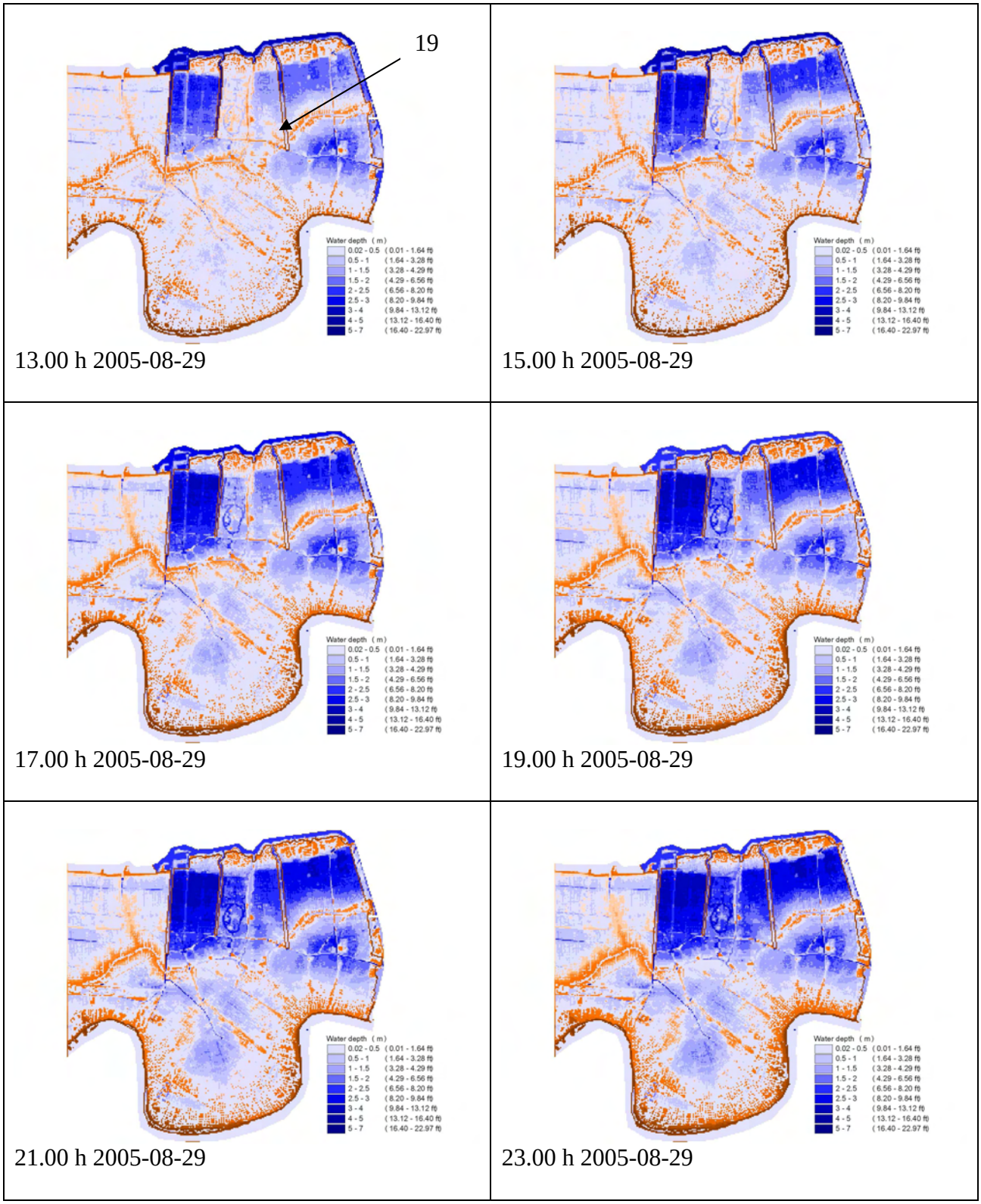


Figure 3.2 Progressing snapshots of the computed water depth inside Orleans Metro bowl

The maximum water depth that occurred in the Orleans Metro bowl is shown in figure 3.3. Figure 3.4 shows the comparison between hydrographs computed by our modeling and hydrographs presented by IPET for the Orleans Metro bowl. IPET apparently based its hydrographs on eye witness accounts, stopped clock times and time/date stamped digital photographs.

There are differences between the model results and the IPET eye witness reports at some locations, but at other locations the results are in agreement. It is important to note that eye witness reports are subjective, and there will always be some uncertainty in eye witness reports given the chaos during a strong hurricane passage, driving rain and wind and the vagaries of the human memory. Additionally, during such extreme events, input data such as the exact water level in the 17th Street before and after the breach, just aren't recoded and generally hard to determine with out direct measuring equipment at the location that can function through a strong storm. Therefore, the differences between the model results and the calibration data are fully acceptable. For the purpose of this study we believe that the model results are very credible.

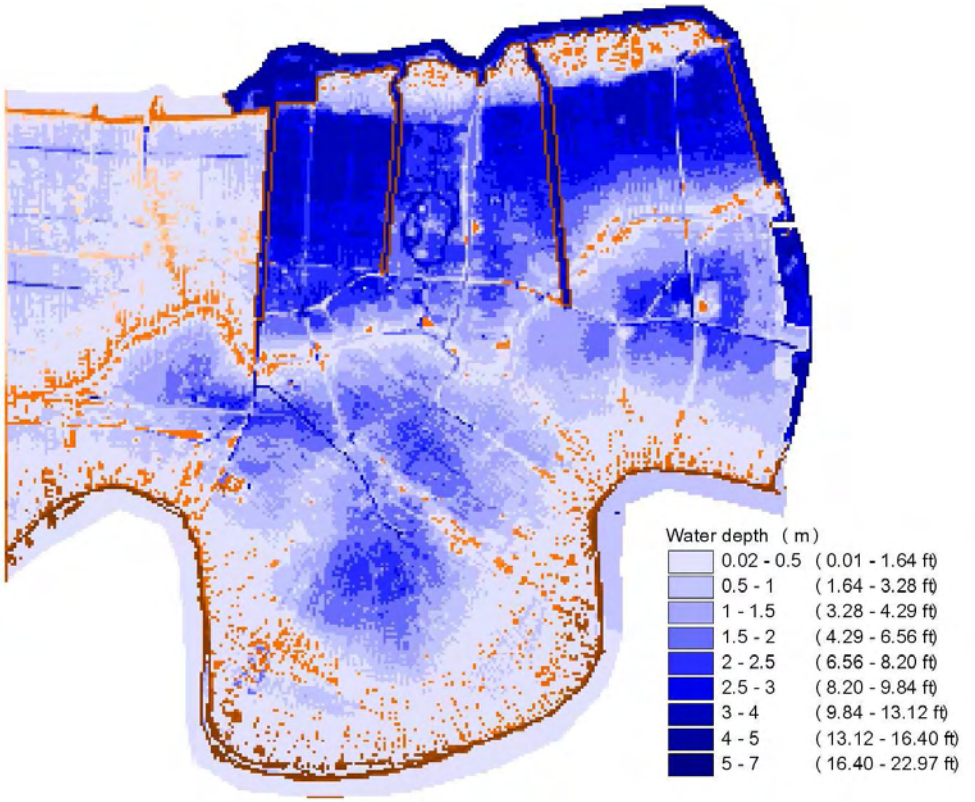
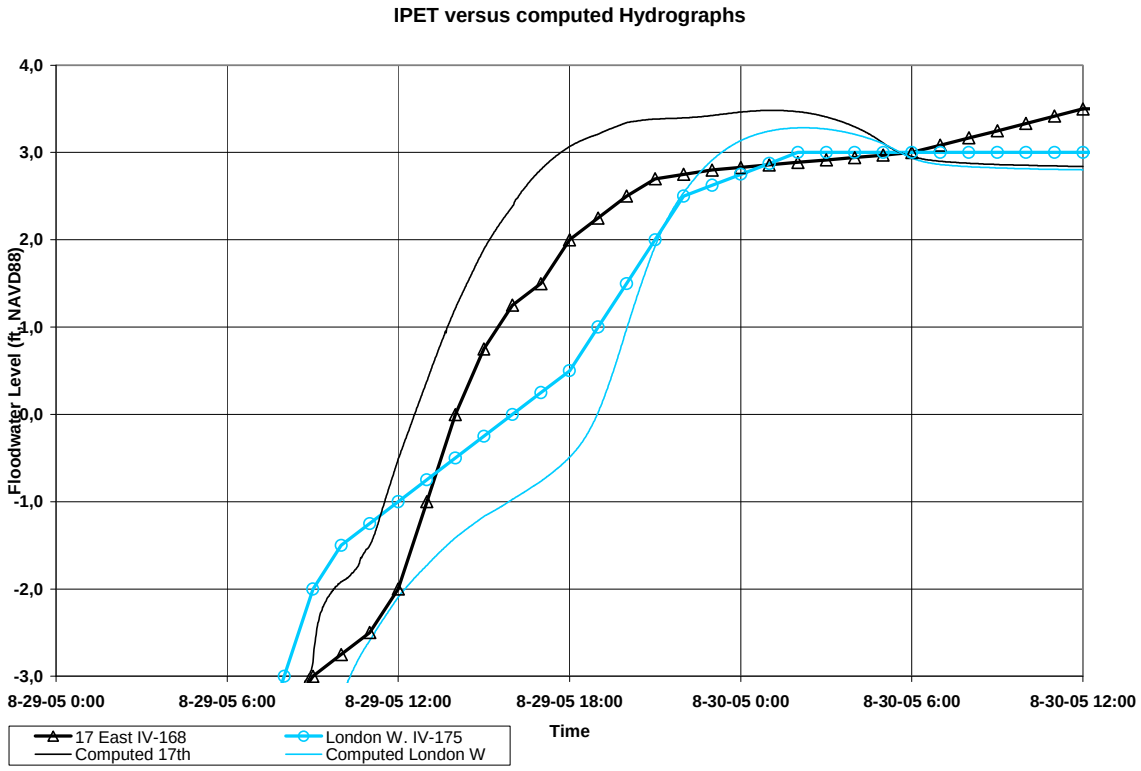


Figure 3.3 Maximum computed flood depths for Orleans Metro bowl as a consequence of the hurricane Katrina flooding event.



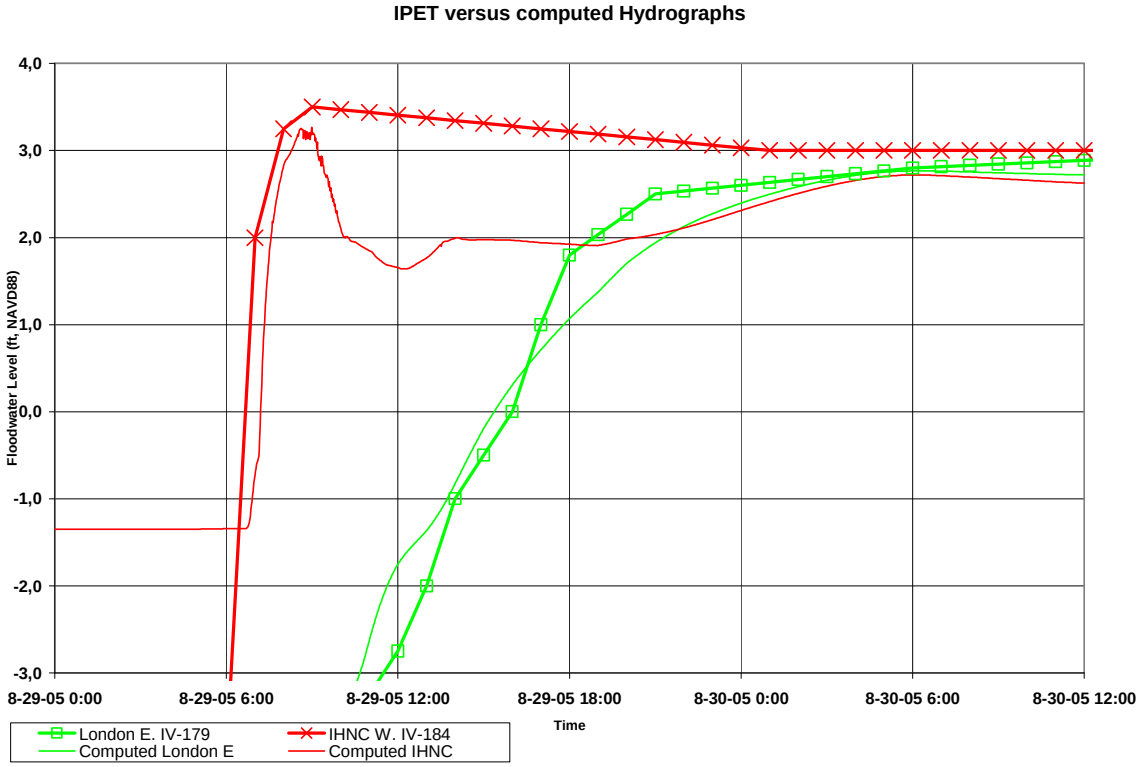


Figure 3.4 Comparison between our computed hydrographs and those presented by IPET, Orleans Metro bowl

3.2 What-if scenarios

In this paragraph several "what-if scenarios" for polder Orleans Metro will be presented. These scenarios will provide more information on the contribution to the flood by the different causes of the flood, like overtopping versus rainfall versus breaching and so on.

Eight sites were chosen in the Metro bowl, some being at very low elevation in the center of bowls, while others were chosen close to internal ridges, i.e., higher ground (figure 3.5). In this way the reader will hopefully better understand the dynamics of the internal flooding of the various New Orleans bowls.

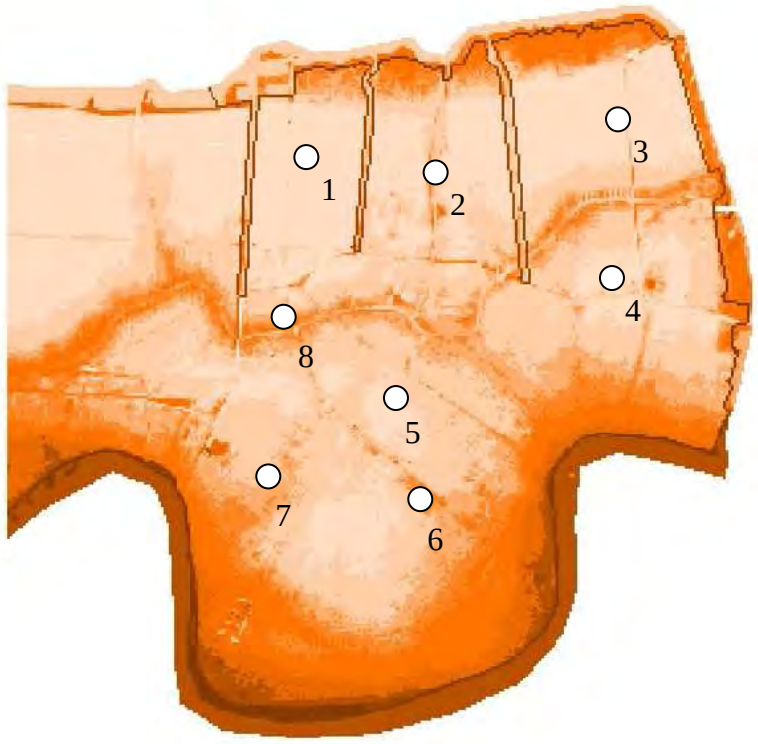


Figure 3.5 Locations utilized for scenario development Orleans Metro bowl.

For each of these eight sites within the Orleans Metro bowl, five different flooding scenarios were modeled, namely:

1) A simulation with all sources of flooding water including rain, pumping, overtopping and breaches. In the following figures the graph or line representing this scenario is labeled **'All causes'.**
2) A simulation without breaches and overtopping but including rainfall and the available pumps operating as they did during hurricane Katrina. In the following figures the graph or line representing this scenario is labeled **'Rain minus available pumps'**.
3) A simulation with no breaches, without overtopping, but including rainfall with the pumps running at 100% efficiency. In the following

figures the graph or line representing this scenario is labeled **'Rain 100% pumps'**.

4) A simulation with only overtopping and including rainfall with the available pumps operating as they did during hurricane Katrina; without breaches. In the following figures the graph or line representing this scenario is labeled **'Overtopping'**.

5) A simulation with all sources of flood water but without the contribution of the 17th Street breach. In the following figures the graph or line representing this scenario is labeled **'No breach 17th street'**.

Description of the scenarios

Scenario 1 (all causes) is the best fit to reality during Katrina, see section 3.1. This scenario takes into account breaches, overtopping, rainfall and the two major pumping stations which were available during Katrina; pumping stations OP 19 and OP I-10 (see table 3.2).

Scenario 2 (rain minus available pumps) represents a scenario with rainfall and only the available pumping stations (OP 19 and OP I-10) during Katrina. The pumping stations have been taking into account by deducting the pump capacity per hour from the rainfall data. This run assumes that once the rain quits, the pumps stop pumping.

Scenario 3 (rain and 100% pumps) represents a scenario with rainfall and the pumping stations in the Metro bowl. It is assumed that they are all working at full capacity, and this represents a lower bound estimate of water levels due to rain. The pumping stations have been taking into account by deducting the pump capacity per hour from the rainfall data. After the rain has stopped, the influence of the pumping stations is estimated with a spreadsheet calculation. This estimate is uncertain, but it will represent a credible estimate of the order of magnitude.

Scenario 4 (overtopping) takes into account overtopping, rainfall and the pumping stations which were available during Katrina; pumping stations OP 19 and OP I-10. The pumping stations have been taking into account by deducting the pump capacity per hour from the rainfall data. This run assumes that once the rain quits, the pumps stop pumping.

Scenario 5 (no breach 17th Street) takes into account all breaches without the flood contribution from the 17th Street breach. It includes also overtopping, rainfall and the pumping stations which were available during Katrina; pumping stations OP 19 and OP I-10. The pumping stations have been taking into account by deducting the pump capacity per hour from the rainfall data. This run assumes that once the rain quits, the pumps stop pumping.

For each location or site given in figure 3.5, the five simulations are plotted below. Note that given the dynamics of the flooding event, the scenarios “Rain minus available pumps” and “Overtopping” are sometimes identical and one curve may mask the other in the figures.

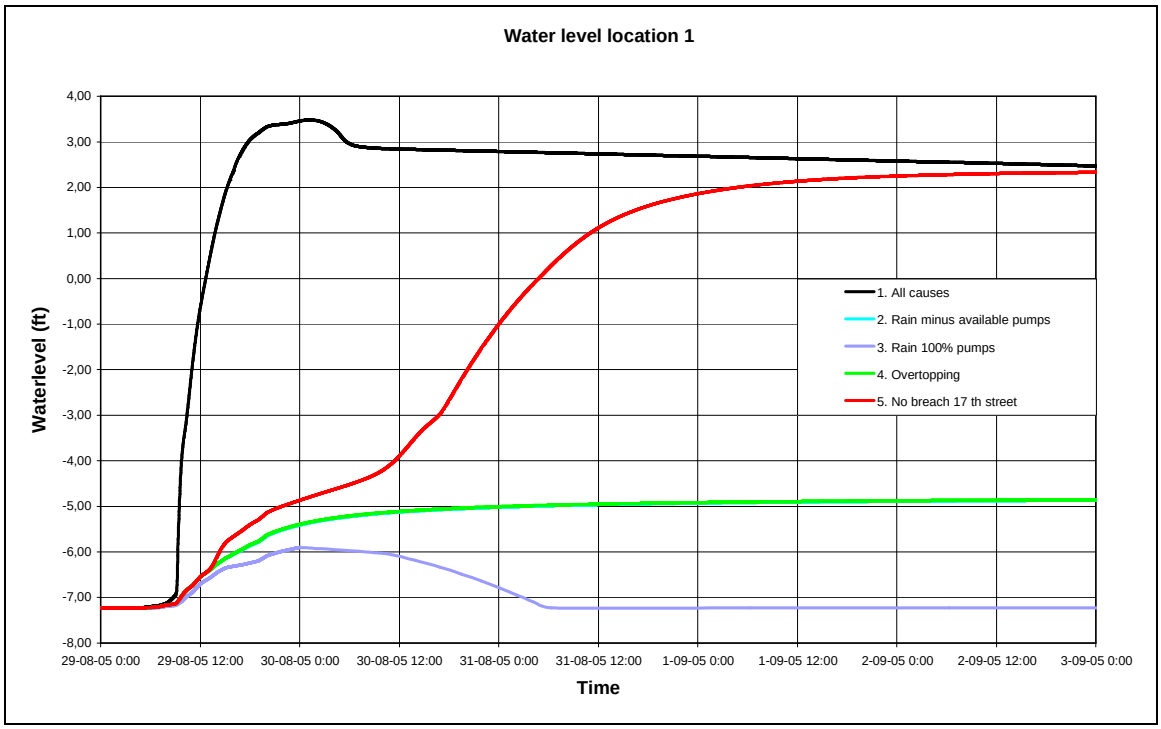


Figure 3.6 Water levels location 1 Orleans Metro. The scenarios ‘Rain minus available pumps’ and ‘Overtopping’ are identical

This site or location (1) is approximately halfway between the 17th Street and Orleans Avenue canals. Here rainfall collects and floods areas lower than minus 5 ft NAVD88. As one would expect the overtopping at the east side levee (at IHNC) has no influence in this area.

Scenario 3, rain with pumps working at 100% capacity while it rains, is a lower bound or bracket for the influence of rain on the internal flood levels, and reveals that areas of the bowl adjacent to site (1) lower than -5.9 ft NAVD88, would have flooded during the storm from rainfall, even if the pumps had worked at maximum capacity. However, if there would have been no overtopping or breaching then this area would have been pumped dry once the rainfall ceased.
If the breach at the 17th Street canal had not occurred, the other breaches would have filled this area, but somewhat later.

Thus in this section of the Orleans Metro bowl during Katrina with the pumps operating at about 50% capacity and being shut down early in the morning because the pump houses flooding after the breaches occurred, 1.8 feet of the 10 feet of standing water was attributable to the rainfall, six inches of the initial flooding being attributable to the pumps not operating at full capacity and at least 7.5 feet (75%) due to the breaches.

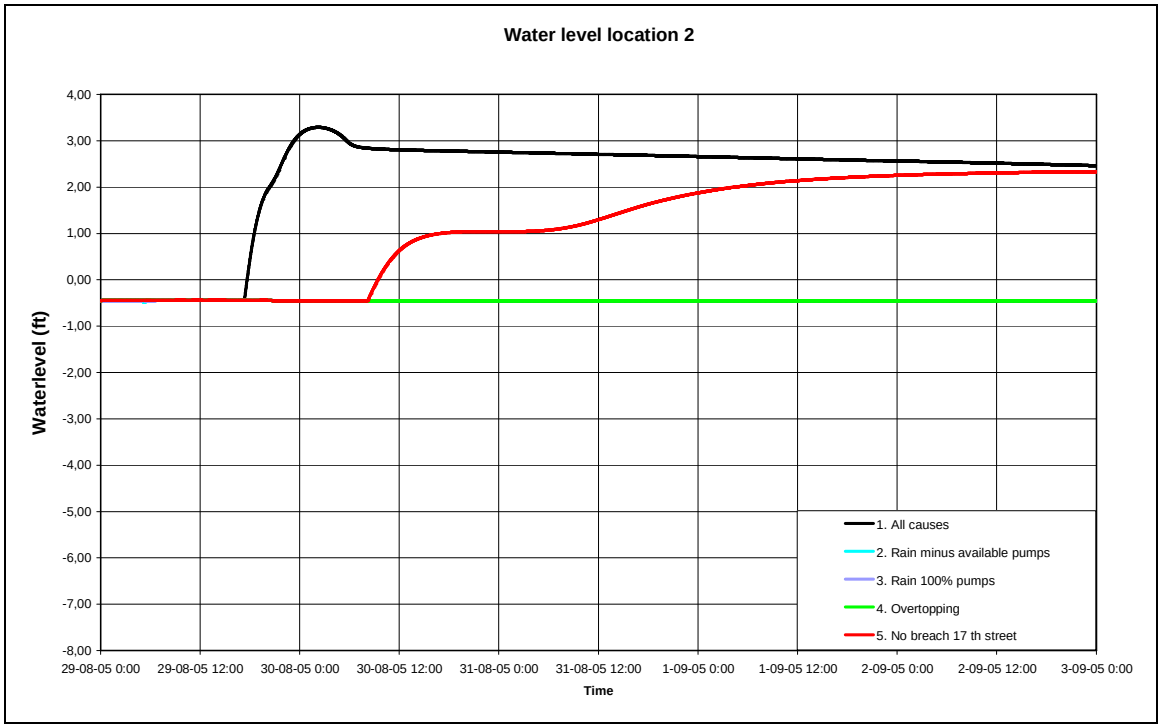


Figure 3.7 Water levels location 2 Orleans Metro. The scenarios 'Rain minus available pumps', 'Rain 100% pumps' and 'Overtopping' are identical

Site 2 is located on higher ground between the Orleans Ave and London Avenue canals. Rainfall does not accumulate at site 2 because of its relatively high elevation (-0.5 ft NAVD88). As one would expect the overtopping at IHNC has no influence at this location.

Thus at this location of the Orleans Metro bowl during Katina there was no flooding attributable to the rain or from the overtopping along the INHC. All the flooding (100%) came from the breaches.

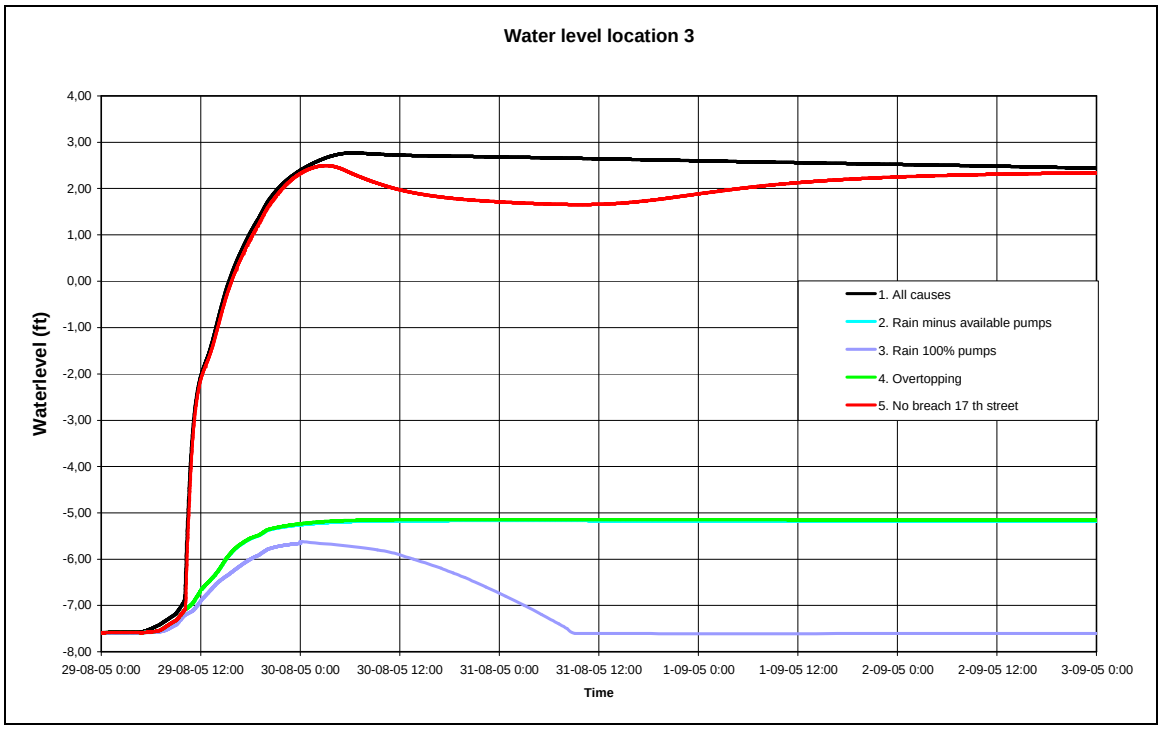


Figure 3.8 Internal flooding levels location 3, Orleans Metro bowl. The scenarios 'Rain minus available pumps' and 'Overtopping' are almost identical

Site 3 is located between the London Avenue canal and the INHC. At this site rainfall only accumulates in areas deeper than -5 ft NAVD88. If the pumps had operated at 100% capacity during the storm rainfall flooding would have been restricted to areas lower lying that minus 5.5 ft NAVD88

The influence of the 17th Street breach is less than at location 1 & 2 and only amounts to approximately six inches of the initial flooding or 5%.

There is minor overtopping south of Interstate 10 from the INHC as can be discerned on figure 3.8, the overtopping line lies just above the rainfall minus the pumps operation line.

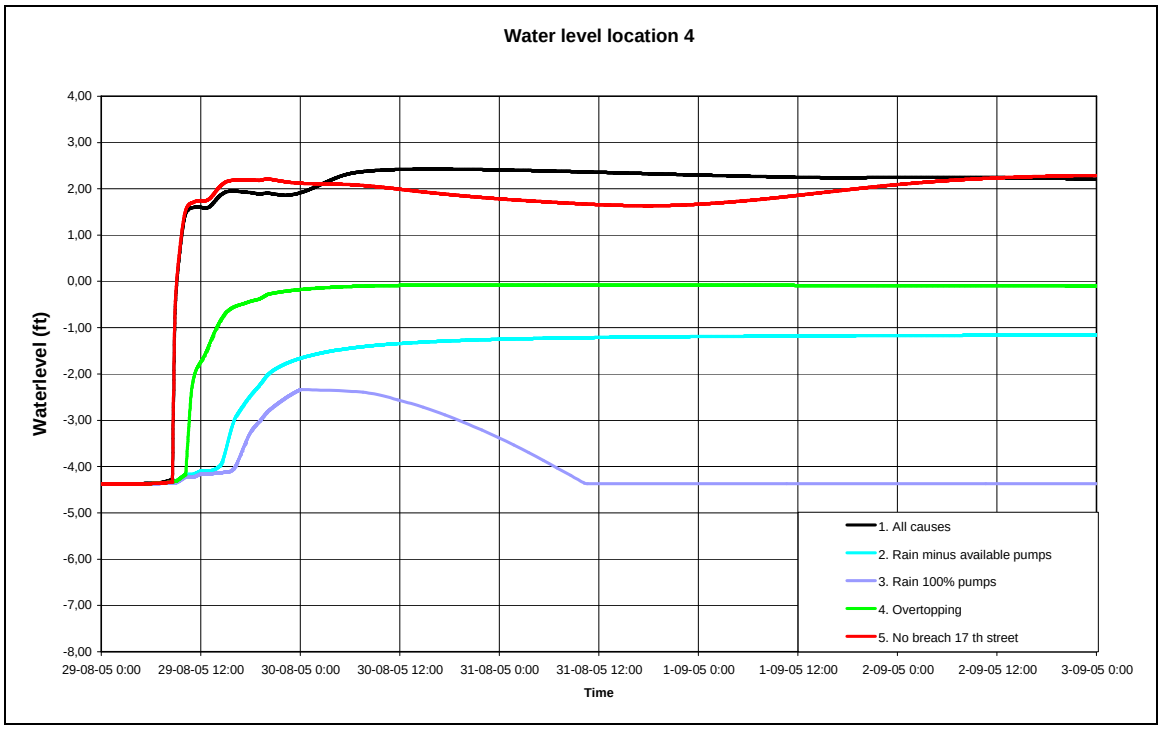


Figure 3.9 Water levels location 4 Orleans Metro

Location 4 is within a bowl within the Orleans Metro bowl bounded by the Mississippi River levee, the INHC and the Metairie-Gentilly Ridge

At location 4, rainfall influences areas lower than -1 ft NAVD88. The influence of the 17th Street breach is less then at location 1 & 2 and only marginal.
In this part of the Central bowl overtopping is more important than elsewhere in the polder. Areas lower than 0 ft NAVD88 would have flooded by this scenario.

Pump OP I-19 situated near the IHNC was available during Katrina. If the pumps had been operating at full capacity while it rained the flooding would have been about one feet lower, assuming the pumps shutdown once the rain ended. However, it is important to know what the flooding would have been if there had been no breaches, no overtopping and the pumps had continued to work after the rain ceased and dewatered the bowl. This is given in the scenario “Rain 100% pumps”.

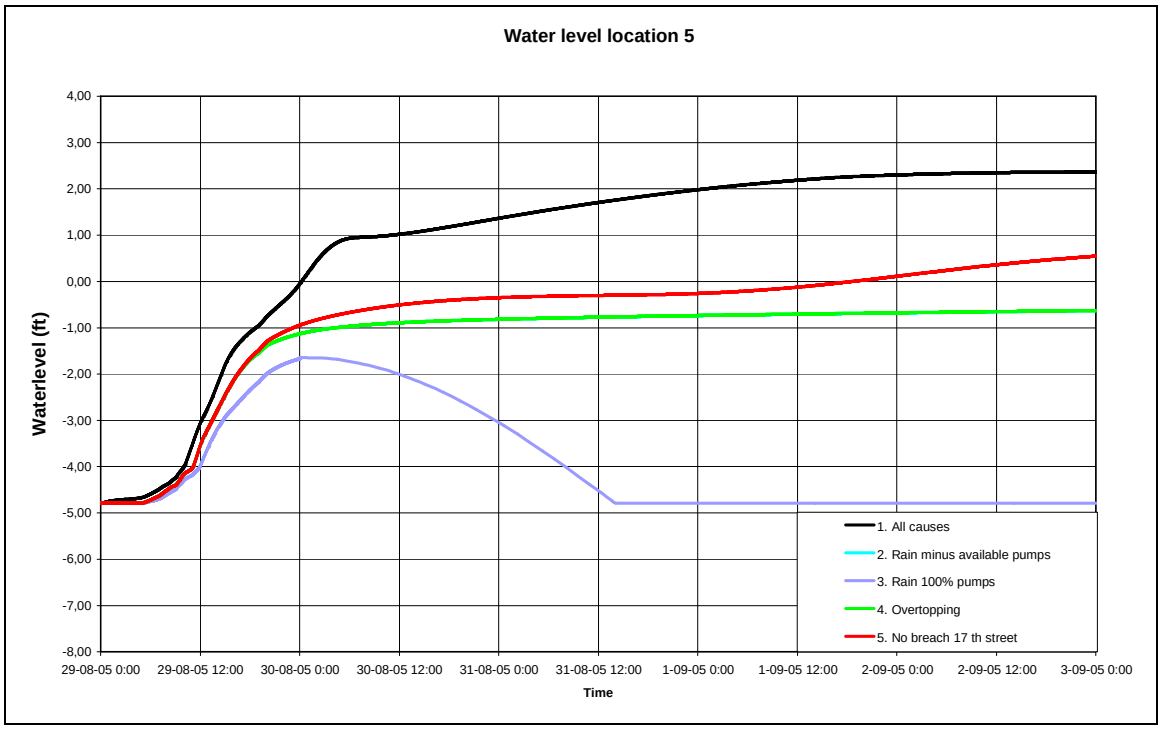


Figure 3.10 Water levels location 5 Orleans Metro, the scenarios 'Rain minus available pumps' and 'Overtopping' are identical

Location 5 is located in a sub-bowl south of the Metairie-Gentilly Ridge. At location 5 rainfall influences area's lower than -0.5 ft NAVD88. Overtopping along the INHC has no influence on flooding at location 5, while the London Avenue breaches have some important influence on the water level.

Location 6 is south of location 5 in the same sub bowl but is higher land. Rainfall accounts for about nine inches of water and based on the internal flooding model most of the flooding comes from the 17th Street Canal breach.

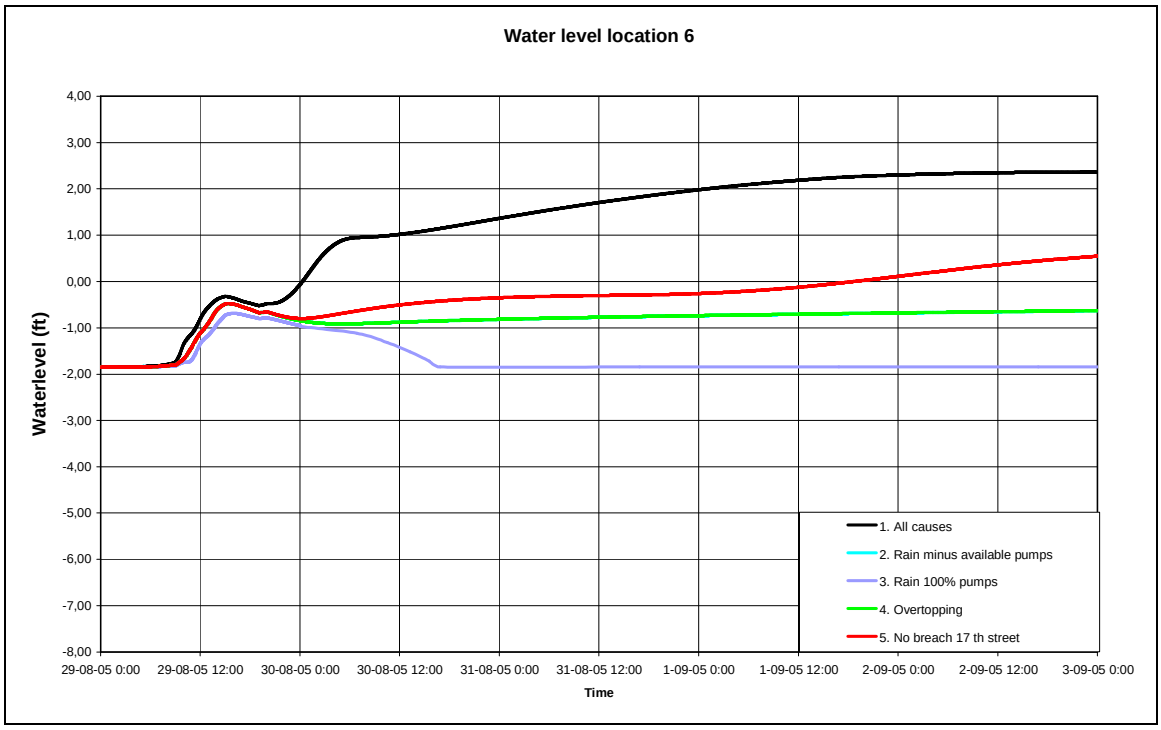


Figure 3.11 Internal flood water levels location 6 Orleans Metro bowl, the scenarios 'Rain minus available pumps' and 'Overtopping' are identical

Pump OP 2 situated in the area of location 5 was not available during Katrina. However, if the pump had worked and the only flood water had been rainfall then pump OP 2 would have dewatered this part of the Metro bowl in about 15 hours.

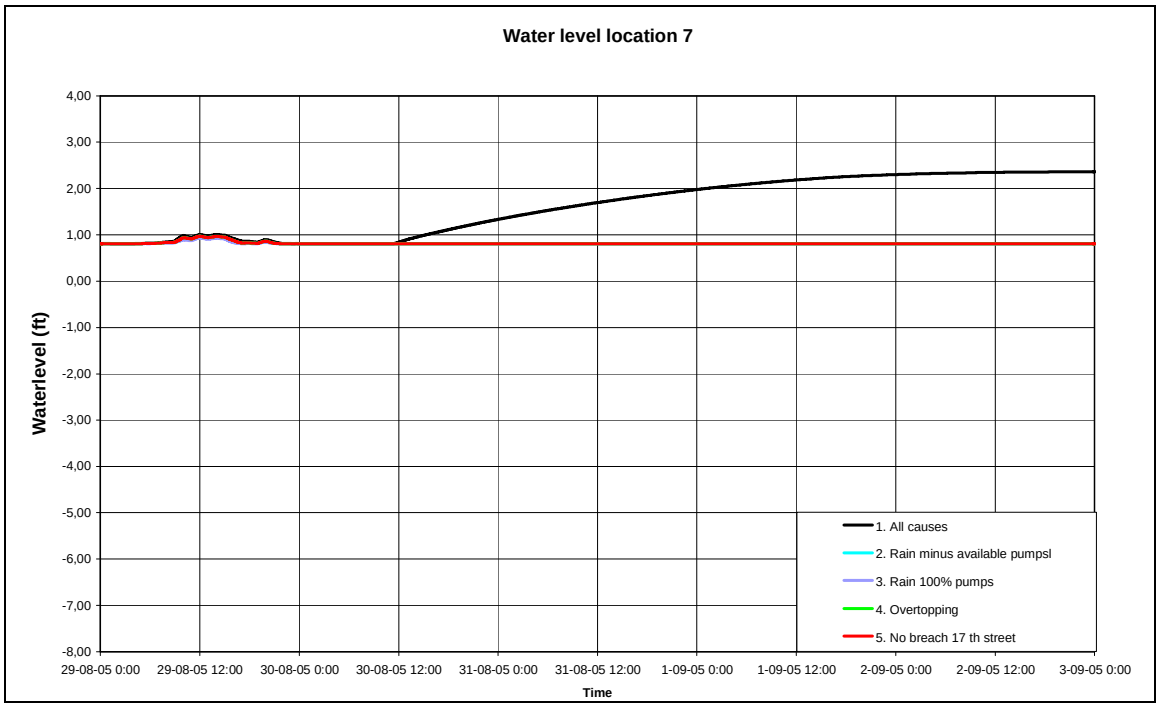


Figure 3.12 Water levels location 7 Orleans Metro, the scenarios ' Rain minus available pumps', 'Rain 100% pumps' and 'Overtopping' are identical

Location 7 is along the western edge of the Metro bowl located on relatively high land compared to say sites 5 and 6. The elevation level of Location 7 is 0.8 ft NAVD88. This site experiences a short period of standing rain water about three inches deep at the maximum and floods predominately from the 17th Street Canal breach. It's interesting to note that the water from the 17th Street breach took almost 24 hours to reach this site and flooded thereafter at a rate of about one foot per day until the water level in the city attained equilibrium with that in Lake Pontchartrain in the early hours of the 2nd September 2005.

Location 8 is on the Metairie ridge (figure 3.13), and at 3.1 ft NAVD88 is some of the highest land in the bowl. The model does indicate that for a period of 10 to 12 hours water did flow over this site, up to about six inches in depth as the flood waters from the 17th Street breach moved south towards sites 5, 6 and 7.

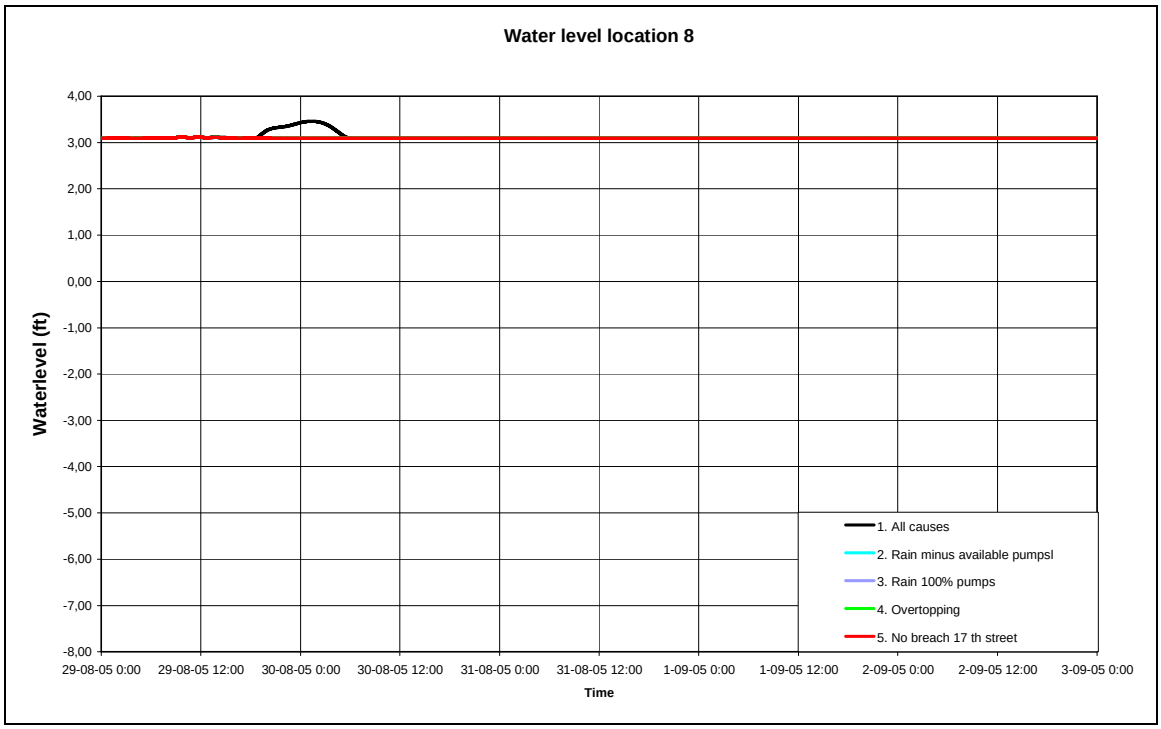


Figure 3.13 Water levels location 8 New Orleans Metro bowl, all the lines are (almost) identical

4 New Orleans East

4.1 Calibration of the model

Figure 4.1 displays the Digital Elevation model (DEM) for the New Orleans East bowl. The star indicates the approximate location of the internal flooding hydrograph used to check the model results. The arrows and numbers correspond to the breaches given in table 4.1. These breaches in combination with the rainfall and water levels as given in section 2.3 and are the basis of the model inputs, along with the DEM, for the New Orleans East bowl.

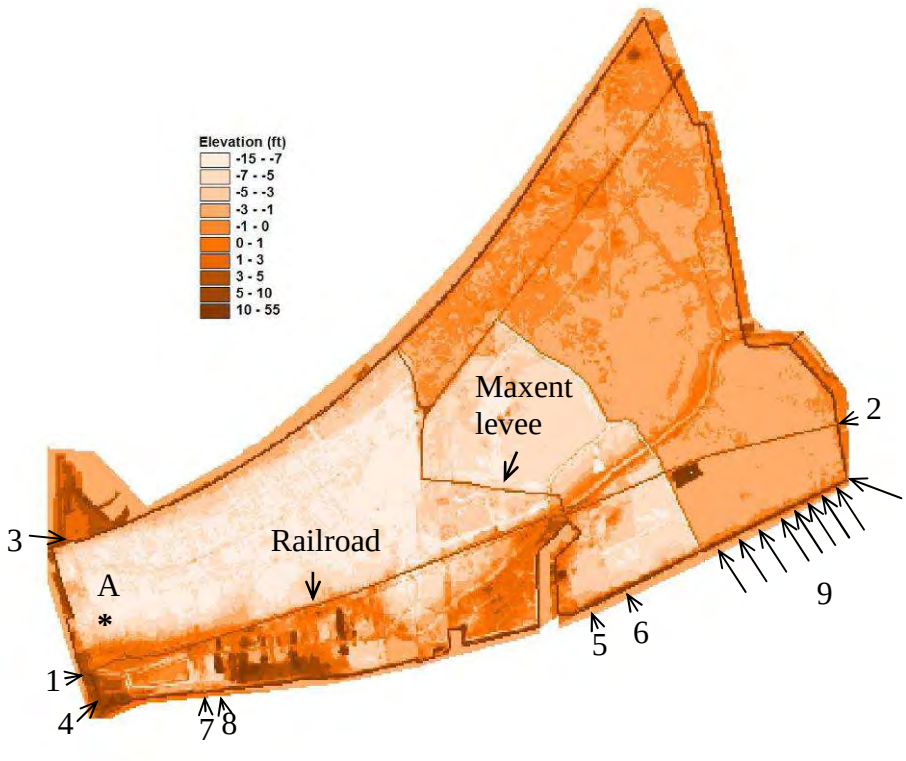


Figure 4.1 DEM New Orleans East bowl including breach (numbers) and the internal flooding hydrograph location (A). Note that this bowl is divided east-west by a railroad embankment and the north-south Maxent levee

Table 4.1: Information on the Breaches in New Orleans East

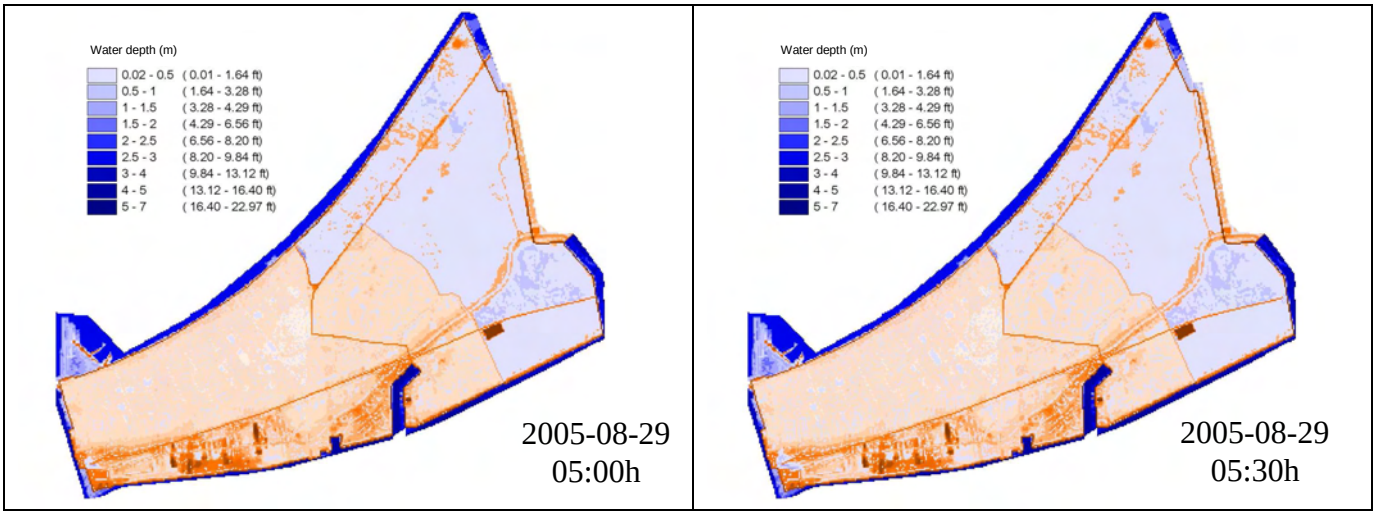
Nr.	Description	Width	Elevation height	Time breach development
1	IHNC East Railroad	61 ft (18.6 m)[1]	Sill elevation +4.5 ft (+1.37 m)[1]	4:30 - 4:45[2]
2	Railroad East	24 ft (7.3 m)[1]	Sill elevation +5.5 ft (+1.67 m)[1]	5:00 - 5:15
3	Airport	33 ft (10 m)[1]	Sill elevation +9.8 ft (+3.00 m)[1]	7:00 - 7:30
4	IHNC East South of RR	25 ft (7.5 m)	Sill elevation +4.9 ft (+1.50 m)[1]	5:00 - 5:15
5	Back levee, East of Michaud Canal 1	112 ft (34 m)[1]	Sill elevation +3.5 ft (+1.07 m)[1]	5:30 - 6:00[2/3]
6	Back levee, East of Michaud Canal 2	34 ft (10.4 m)[1]	Sill elevation +8.4 ft (+2.56 m)[1]	5:30 - 6:00[2/3]
7	Citrus Back levee near Elaine St. West	406 ft (123.5 m)[1]	Sill elevation +11 ft (+3.35 m)[1]	7:00 - 7:30[4]
8	Citrus Back levee near Elaine St. East	615 ft (187.5 m)[1]	Sill elevation +8.5 ft (+2.59 m)[1]	7:00 - 7:30[4]
9	Overtopping New Orleans Back levee (erosion crest)	Approximately 6000 ft in length extending from B. Sauvage towards the Michaud Canal. Position and width based on GIS data[1]	Differences in sections extending from B. Sauvage towards Michaud Canal; Erosion levels based on GIS data[1]	5:30 - 6:00[2/3]

[1] Source: GIS data with positions, widths and sill elevation heights of the breaches [delivered by Chad Morris 28-6-2007]
[2] Source: Team Louisiana report table 3, page 54-55 and timeline page 93-94 [4]
[3] Source: Independent Levee Investigation Team (ILIT), page 7-5 [5]
[4] Source: Independent Levee Investigation Team (ILIT), page 7-6 [5]

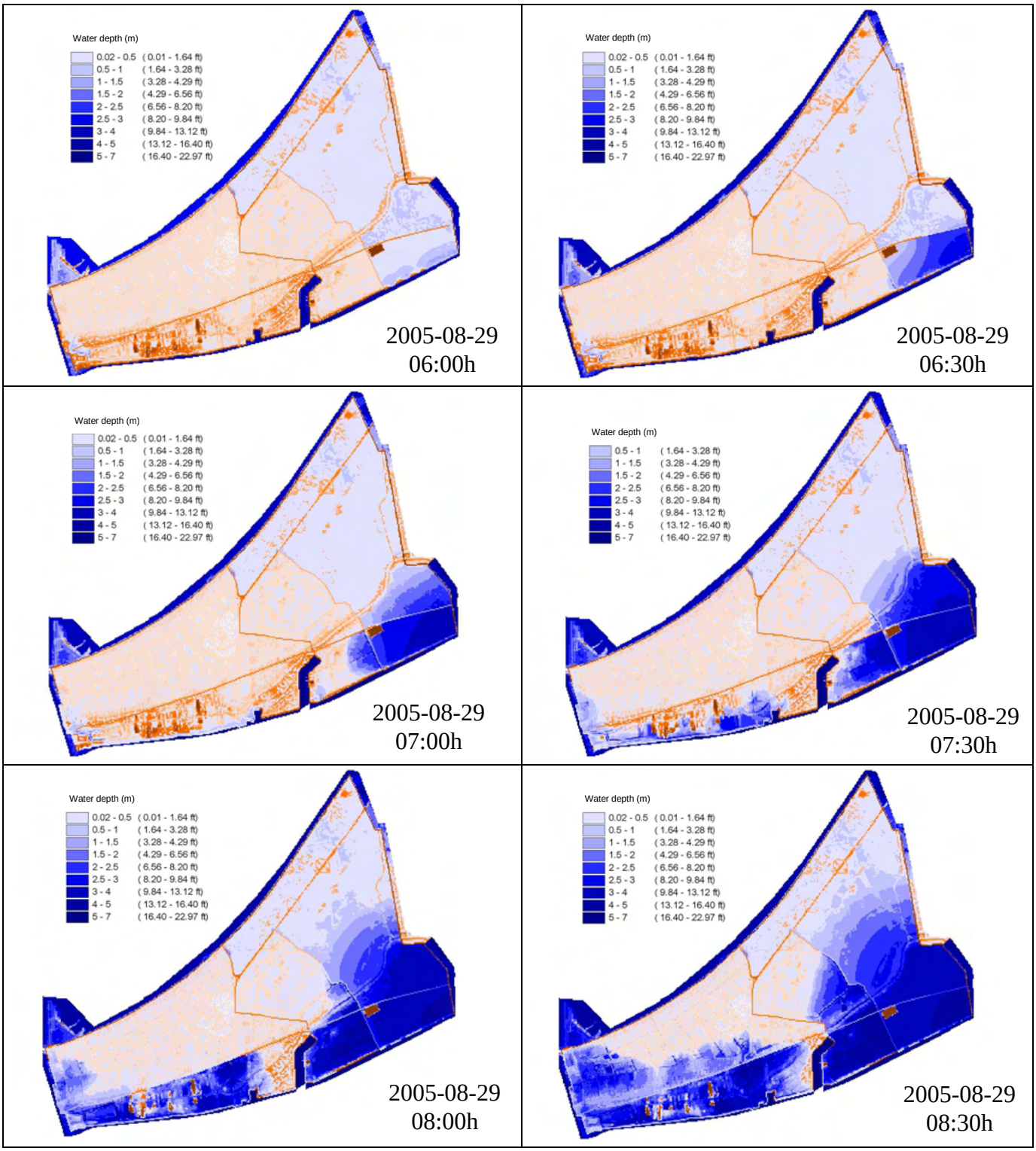
Calibration results

The image series below shows the progression of the simulated internal flood over time (figure 4.2). The first image is a snapshot from August 29th at 5:00am; it shows only minor rainfall and a small breach in the IHNC at the location where the railroad goes through the levee. In the next hour the Back Levee begins to be overtopped and starts to erode. This is consistent with the IPET, Team Louisiana and the ILIT reports, all of which stated that the overtopping and erosion of the New Orleans East back levee started between 5:00 and 6:00am. At 7:00am the water levels in the GIWW and IHNC start to overtop the Citrus Back and IHNC levees. In the Team Louisiana and ILIT report this overtopping initiated at approximately 7:00am, while the IPET report states that the overtopping started earlier at 6:00am.

In the IPET report an eyewitness states that the water was flowing over the east-west railroad line from south to north between 6:30 and 7:00am[1]. In the simulation the water crosses the railroad line between 7:30 and 7:45am. One of two eyewitnesses[2] situated at the west side of the New Orleans East bowl states that between 6:30 and 7:30am the water started to rise rapidly. The other eyewitness states that the flood started between 7:30 and 8:00am. The simulated flood shows that the water started to rise at those locations between 7:30 and 8:00am.
According to eyewitness reports in the northwestern corner of the New Orleans East bowl[3] the flood started between 8:00 and 10:00am. In the simulation the flooding starts at these locations between 7:45 and 8:30am. Again it's important to note that eye witness reports are very subjective, and there will always be some uncertainties given the chaos during a strong hurricane passage; low visibility due to driving rain and wind; and the vagaries of the human memory especially in highly stressful conditions.



[1] Source: IPET volume IV: The Storm, page 191-192 eyewitness at location 3 [1]
[2] Source: IPET volume IV: The Storm, page 191-192 eyewitness locations 5 and 6 [1]
[3] Source: IPET volume IV: The Storm, page 191-192 eyewitness locations 7 to 11 [1]


Water depth (m)
0.02 - 0.5 (0.01 - 1.64 ft)
0.5 - 1 (1.64 - 3.28 ft)
1 - 1.5 (3.28 - 4.29 ft)
1.5 - 2 (4.29 - 6.56 ft)
2 - 2.5 (6.56 - 8.20 ft)
2.5 - 3 (8.20 - 9.84 ft)
3 - 4 (9.84 - 13.12 ft)
4 - 5 (13.12 - 16.40 ft)
5 - 7 (16.40 - 22.97 ft)
2005-08-29 06:00h
2005-08-29 06:30h
2005-08-29 07:00h
2005-08-29 07:30h
2005-08-29 08:00h
2005-08-29 08:30h

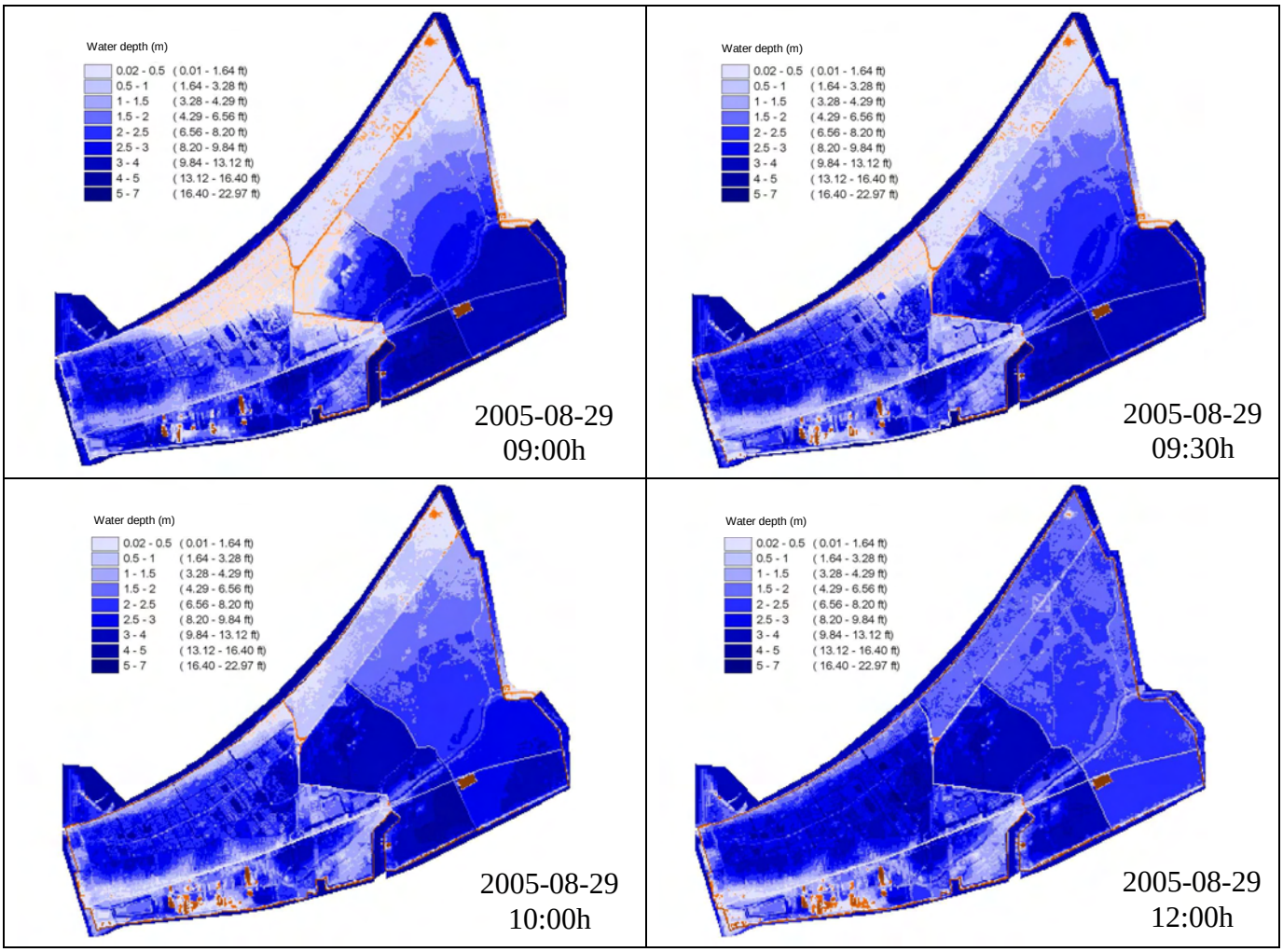


Figure 4.2 Progressing snapshots of the computed water depth inside New Orleans East

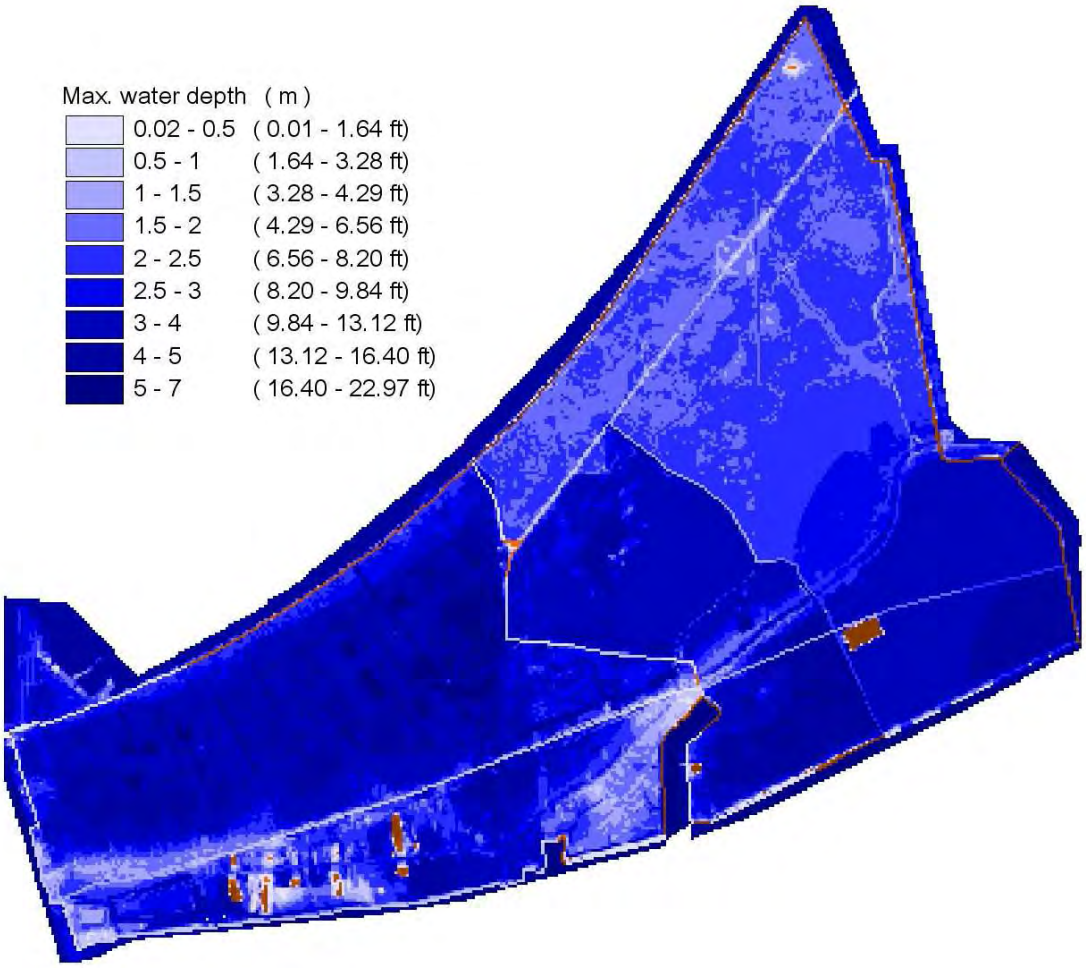


Figure 4.3 Maximum computed internal flood depths as a consequence of the hurricane Katrina related flooding, New Orleans East bowl.

Figure 4.3 shows the calculated maximum internal flood depths in the New Orleans East bowl as a consequence of the hurricane Katrina related flooding.

In the western part of the bowl IPET constructed a hydrograph on basis of eyewitness account and surveyed elevations at location 'A' in figure 4.1. This hydrograph is presented in figure 4.4. The simulated water level based on our modeling is also shown in this figure. Between 11:00am and 12:00pm the water levels diverge, in the simulation the second peak in the water level is caused by the flood water coming from the overtopping of the New Orleans East Back levee. The model results thus reveal some of the complexities of the flooding event not discernable from measurements collected some time after the event.

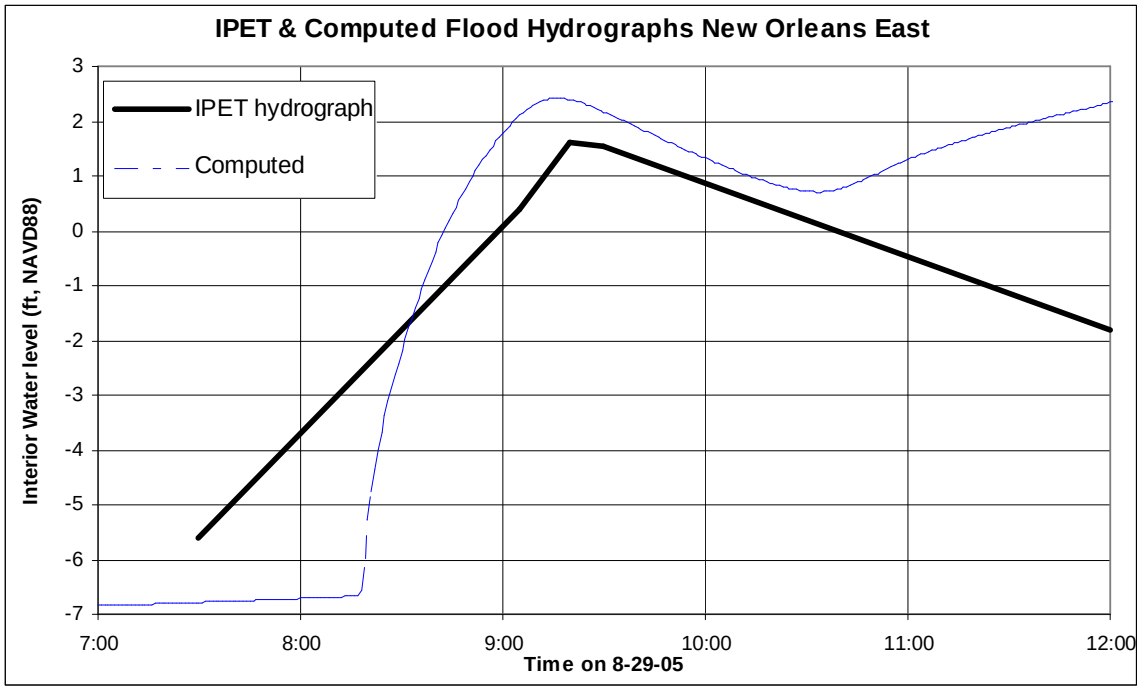


Figure 4.4 Comparison model simulated and IPET flood hydrographs, New Orleans East bowl.

As discussed previously, in extreme events such as Katrina it is difficult if not impossible to get direct measurement of some input data such as water levels at the time of a breach, especially right at the breach location. However, the differences between the computer model results and the calibration data are fully acceptable. For the purpose of this study the model results are very credible.

4.2 What-if scenarios

In this paragraph several "what-if scenarios" for the New Orleans East bowl will be presented. These scenarios will provide more information on the contribution to the flood by the different causes of the flood, like overtopping versus rainfall versus breaching and so on.

Five (5) different scenarios were modeled for the New Orleans East bowl, namely:

1) Scenario all causes and represented by the curve '**All Causes',**
2) Scenario without breaches (inclusive overtopping and rainfall) and represented by the curve or line '**No Breaches'**,
3) Scenario only overtopping (without breaches and without rainfall) and represented by the curve '**Only Overtopping'**
4) Scenario only rainfall without pumps (without breaches and without overtopping) represented by the curve marked '**Rain no pumps'**, and
5) Scenario only rainfall with 100% pump capacity (without breaches and without overtopping) represented by the curve '**Rain 100% pumps'**.

Scenario 1 is equal to the Katrina event. Scenario 2 is the Katrina event without any breaches, only overtopping of the pre-Katrina levees/flood walls and rainfall contribute to the flooding. In scenario 3 only overtopping of the pre-Katrina levees/flood walls is considered. Scenarios 4 and 5 show the upper and lower bound or brackets of the water levels in the situation if flooding had only being due to rainfall and there had been no breaches and/or overtopping. Scenario 4 shows the water levels with only rainfall, when no water is pumped out (upper bound of the water levels due to rainfall). Scenario 5 shows the water levels with only rainfall, when all pumps in New Orleans East function at 100% of their rated pump capacity according to IPET [3]. During Katrina the pumps did not function in New Orleans East [3].

At five locations in the bowl, indicated in figure 4.5, water level changes have been measured for each of the five scenarios.

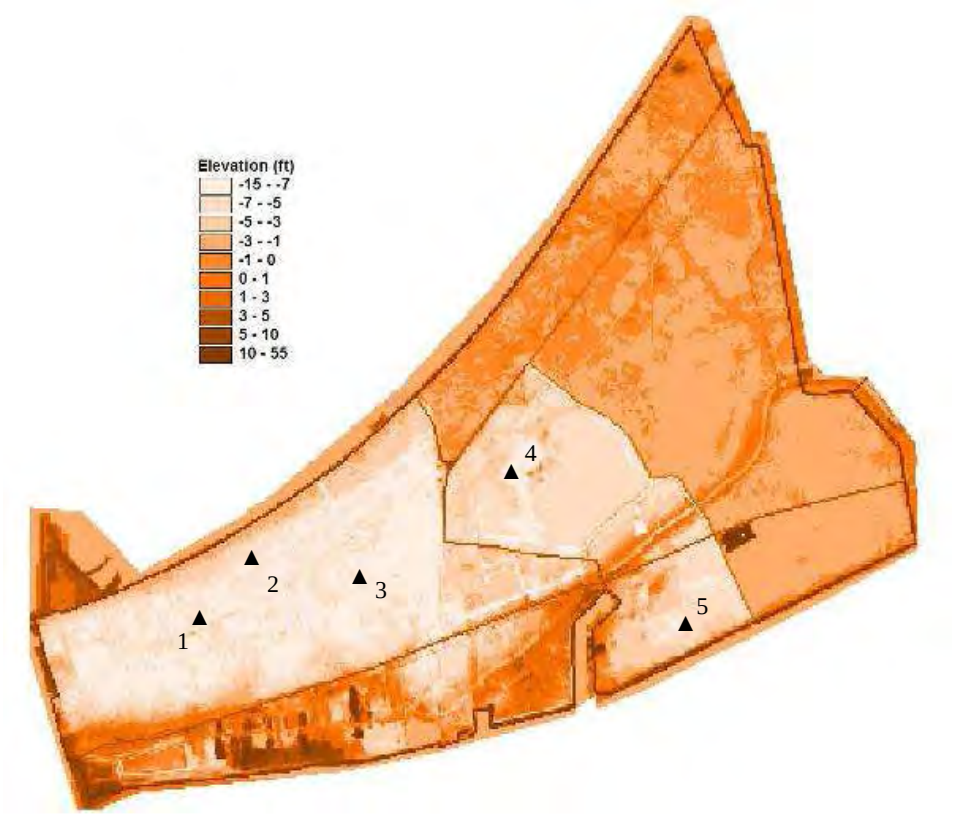


Figure 4.5 Water level locations scenario runs New Orleans East

Figures 4.6-4.10 show the changes in water levels on the five locations. The difference between the black solid and orange dashed line is caused by the breaches and erosion that occurred during the storm. The difference between the black line and the green dashed-dot line is caused by the breaches and rainfall. The difference between the green dashed-dot line and the orange dashed line is the water that comes into the polder due to rainfall.

The scenarios show that overtopping and breaches are the main causes of flood water in New Orleans East. Along the east side (Willow Brook & Six Flags - sites 4 and 5) the flooding is dominated by the breaches in the Back levee. The inner levee (Maxent Levee) does create two compartments within the polder. Along the west side of the New Orleans East bowl overtopping and breaching appear to contribute almost equal amounts to the flooding, with overtopping dominating.

Rainfall has a smaller influence on the final water level in this bowl than overtopping or the breaches. The lower bound approach for the contribution of rainfall flooding (scenario 5 - only rain with 100% pump capacity) shows no substantial rain water at these five locations. Also in the upper bound approach (scenario 4 - only rain without pumps) there is not much rainwater at these locations.

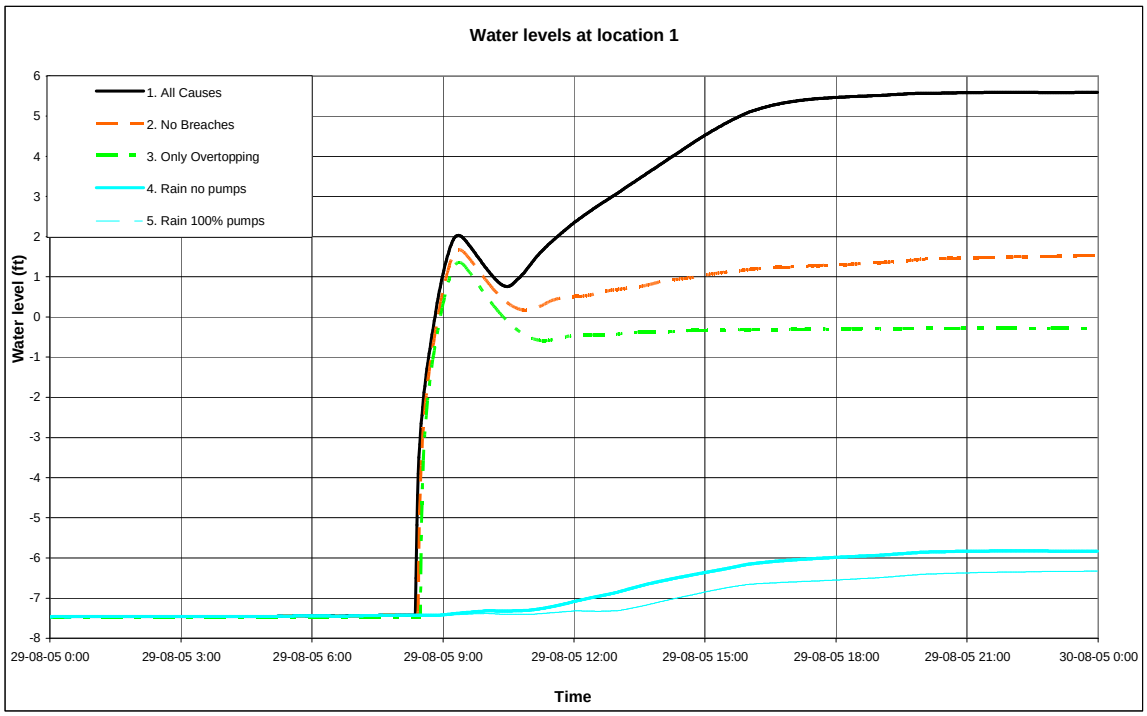


Figure 4.6 Water levels location 1 New Orleans East

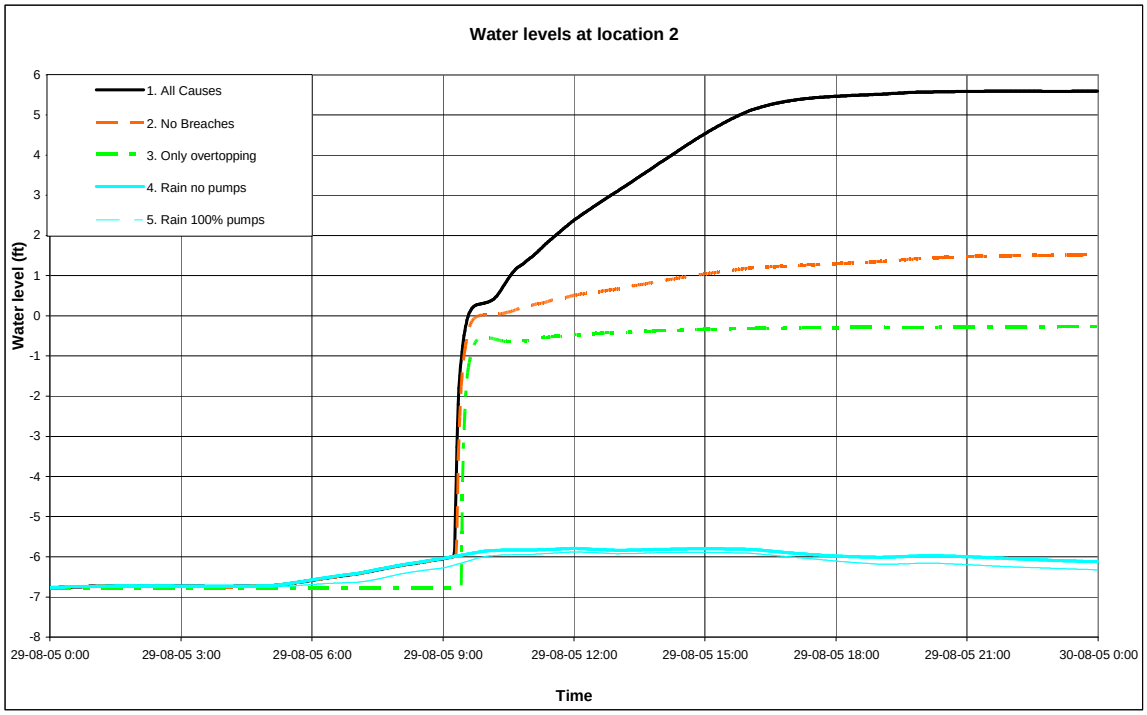


Figure 4.7 Water levels location 2 New Orleans East

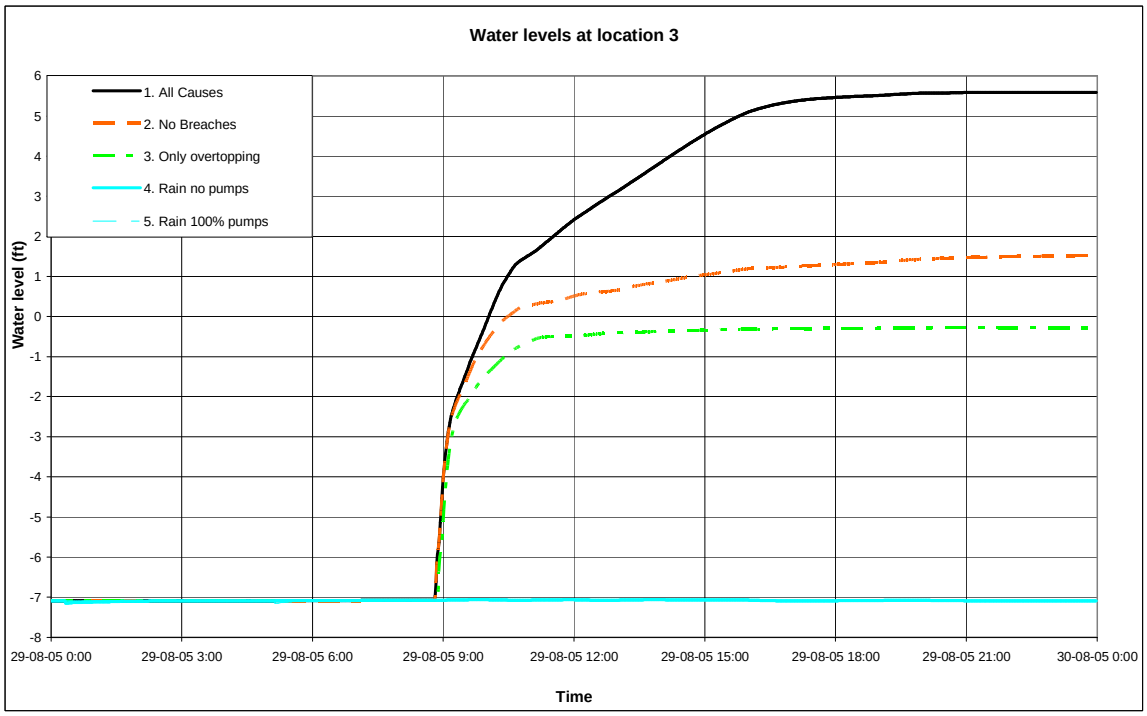


Figure 4.8 Water levels location 3 New Orleans East, the blue dashed line lies under the blue solid line

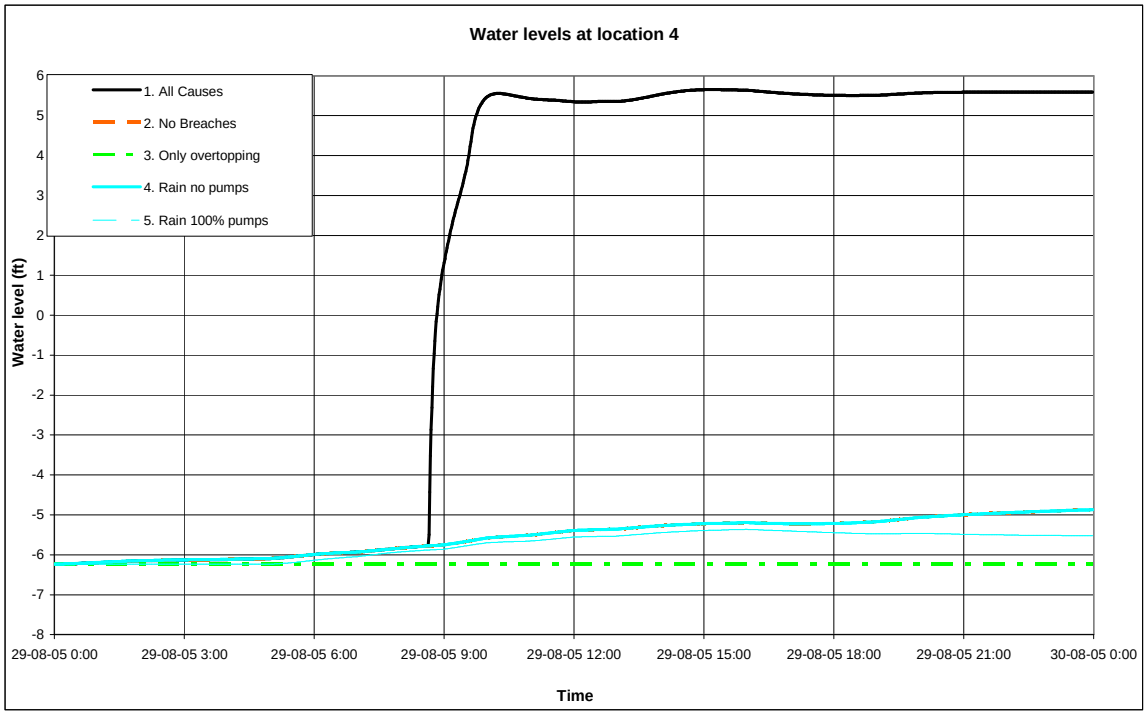


Figure 4.9 Water levels location 4 New Orleans East

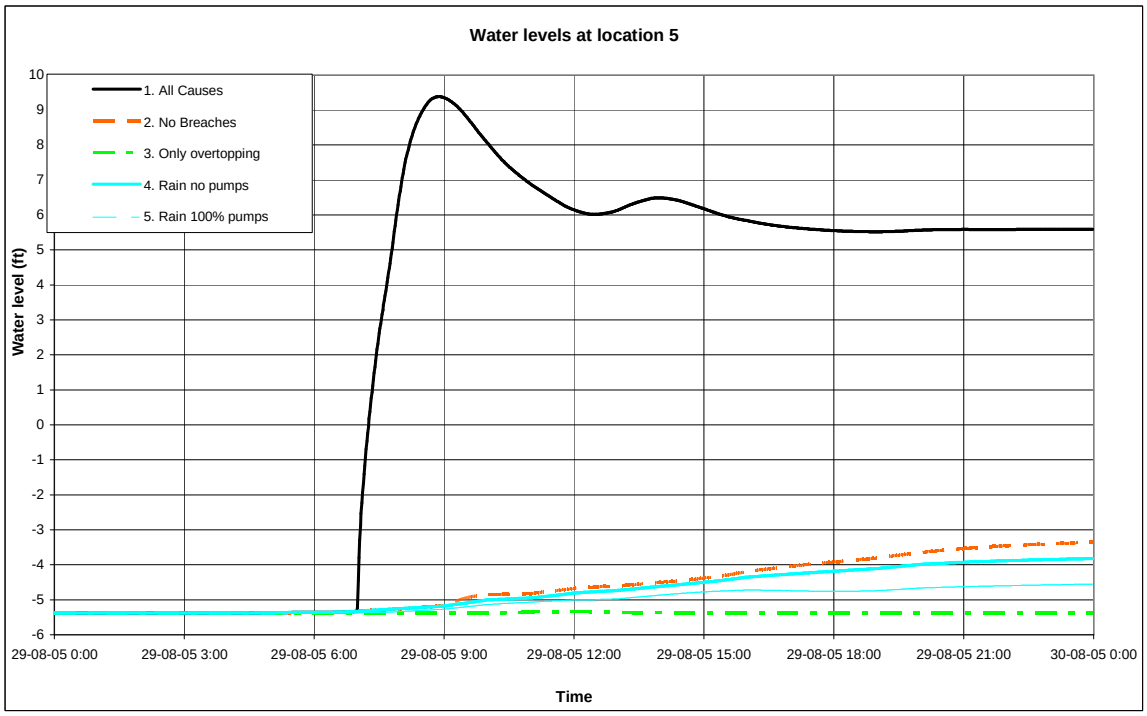


Figure 4.10 Water levels location 5 New Orleans East

5 Saint Bernard

5.1 Calibration of the model

Figure 5.1 shows the Digital Elevation model (DEM) for the St. Bernard bowl. The three stars indicate the approximate locations of the internal flooding hydrographs used to check the model results. The arrows and numbers correspond to the breaches given in table 5.1. These breaches in combination with the rainfall and surge hydrographs outside the bowl, as presented in section 2.3, are the basis of the model inputs, along with the DEM, for the New Orleans East bowl. This bowl is divided into two parts by an internal levee, the 40-Arpent levee. To the east there is a large wetland, 30,000 acre plus basin or bowl and to the west the inhabited part of this parish. The crest height of the 40-Arpent levee between the wetlands and populated areas is 6.5 ft.

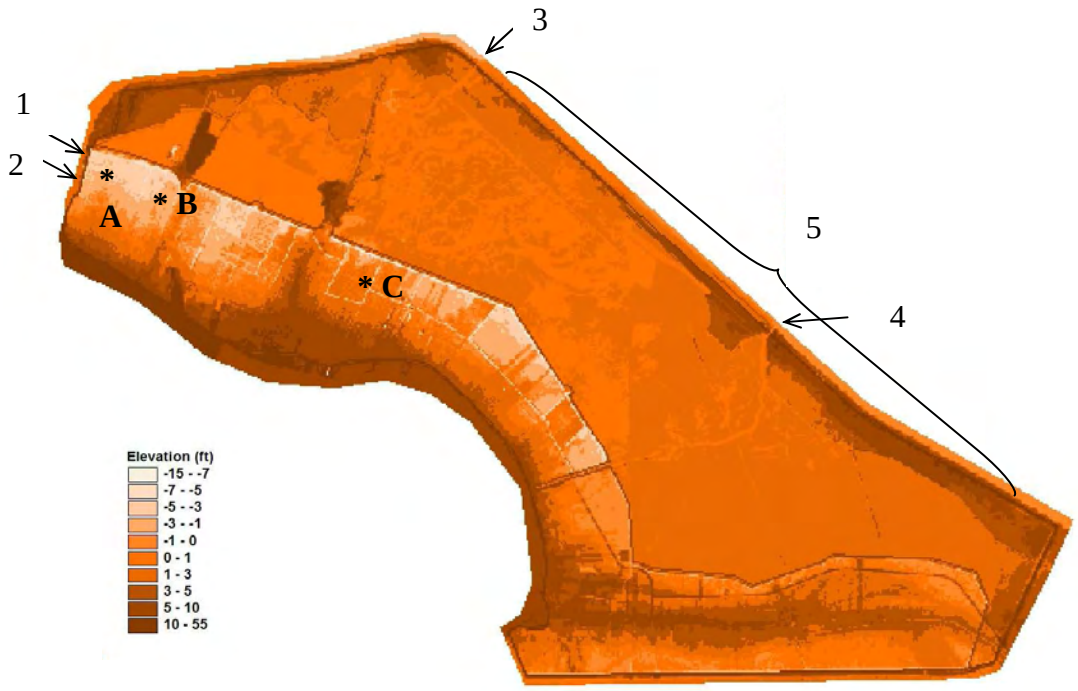


Figure 5.1 DEM St. Bernard, including breach (numbers) and internal hydrograph locations (letters)

Table 5.1 Information on the Breaches in St. Bernard

Nr.	Description	Width	Elevation height	Time breach development
1	IHNC North	221 ft (67 m)[1]	Sill elevation +1 ft (+0.3 m)[1]	7:00 - 7:30[2]
2	IHNC South	808 ft (274 m)[1]	Sill elevation +1 ft (+0.3 m)[1]	7:00 - 7:30[2]
3	MRGO Bayou Bienvenue	214 ft (65 m)[1]	Sill elevation -6 ft (-1.8 m)[1]	5:00 - 8:30[3]
4	MRGO Bayou Dupree	54 ft (17 m)[1]	Sill elevation -6 ft (-1.8 m)[1]	5:00 - 8:30[3]
5	Overtopping MRGO levee (erosion crest)	Various sections along MRGO levee; position and width based on GIS data[1]	Various sections along MRGO levee; erosion levels based on GIS data[1]	5:00 - 8:30[3]

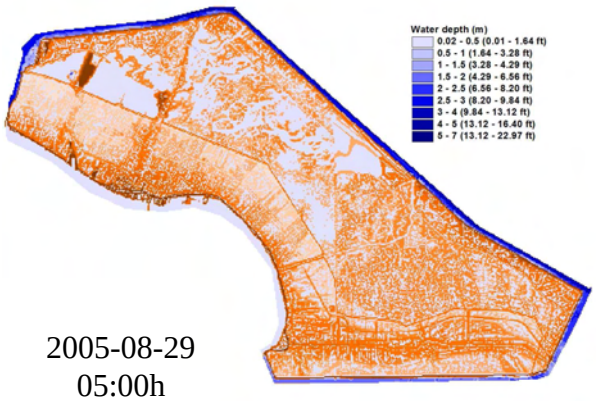
Calibration results

The time progressive image snapshot series shows how this bowl flooded during hurricane Katrina. The first image in figure 5.2 is a snapshot from August 29th at 5:00am; it shows only minor rainfall. Between 5:00 and 8:30am the erosion of the MRGO levee takes place, and after 6:30am substantial volumes of surge water from the MRGO flow into the wetlands bowl between the MRGO and 40-Arpent levee. In the simulation the 40-Arpent levee starts to overflow at 8:00am and at 8:30am the first water enters Chalmette from a northeastern direction as a consequence of overtopping the 40-Arpent levee. IPET in their report state this overtopping starts at about 8:20am[4], which is in agreement with Team Louisiana's 8:30am[5]. IPET also reports that Chalmette flooded from the northeast, strong agreement with the simulation results.

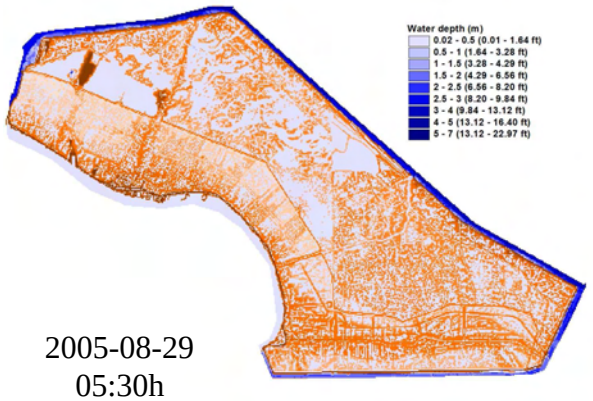
At 7:00am the North and South breaches from the IHNC channel into the Lower Ninth Ward start to develop and at 7:30am the first flooding of the Lower 9th Ward is seen in the model time-step images of the internal flooding. This timing is in agreement with both the ILIT and Team Louisiana reports. IPET has another opinion about the North breach and states that this breach started earlier, but both ILIT and Team Louisiana contradict this conclusion. IPET mentions that surge water started to enter the Lower 9 Ward before 5:30am[6] and Team Louisiana around 6:00am. Potential sources of this early internal flooding include overtopping of the IHNC floodwall, the two breaches in the IHNC floodwall, and flow from the overtopping of the MRGO/GIWW levees.

[1] Source: GIS data with positions, widths and sill elevation heights of the breaches [delivered by Chad Morris 2007-6-28]
[2] Source: Team Louisiana report table 3, page 54-55 and timeline page 93-94 [4]
[3] At 5:00 waves start to erode the MRGO levee [Source: see footnote 2], in the simulation erosion continues until the peak water level in Lake Borne is reached at 8:30.
[4] Source: IPET volume IV: The Storm, page 199 [1]
[5] Source: Team Louisiana, page 64 [4]
[6] Source: IPET volume IV: The Storm, page 200 [1]

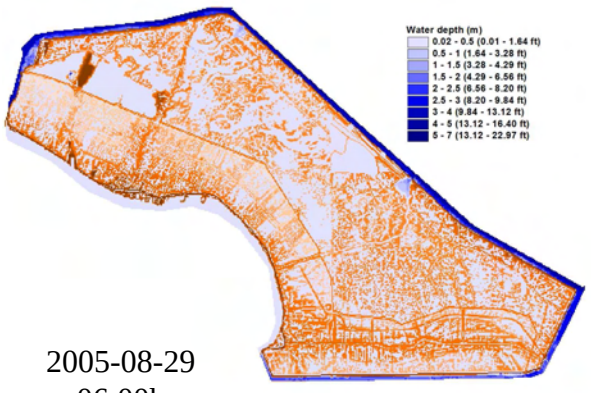
In our model simulations no overtopping occurs before 7:00am, and the two breaches start at 7:00am. Therefore no water, except rain water, prior to 7:00am is visible inside the Lower 9th Ward in the simulation results. ILIT gives an alternative explanation for the early water mentioned by eye witness reports in IPET. ILIT mentions under seepage, water migrating from the channel, under pressure, beneath the IHNC floodwalls as a possible explanation for the early flood water in the Lower 9th Ward. Under seepage through a levee is not captured in the simulation.



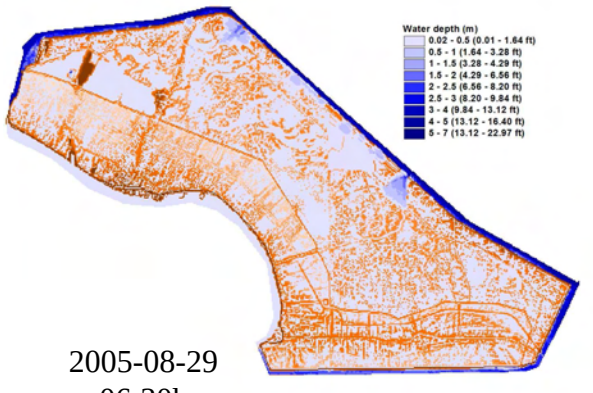
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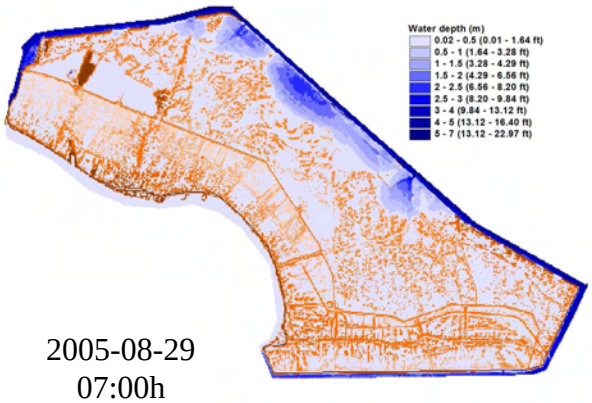
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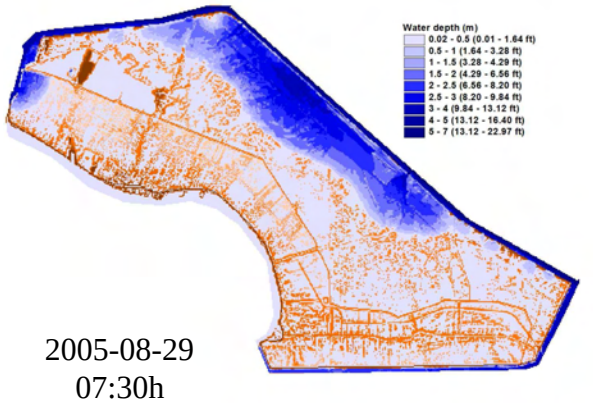
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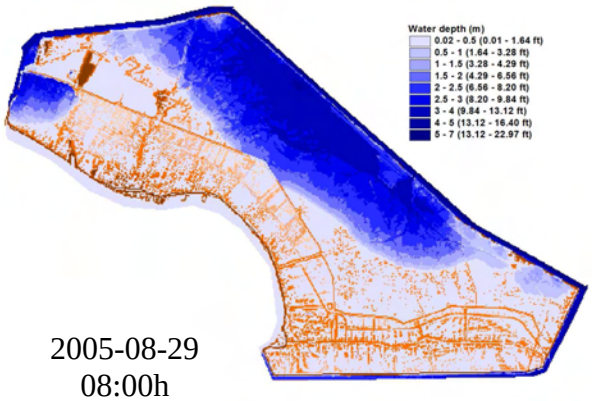
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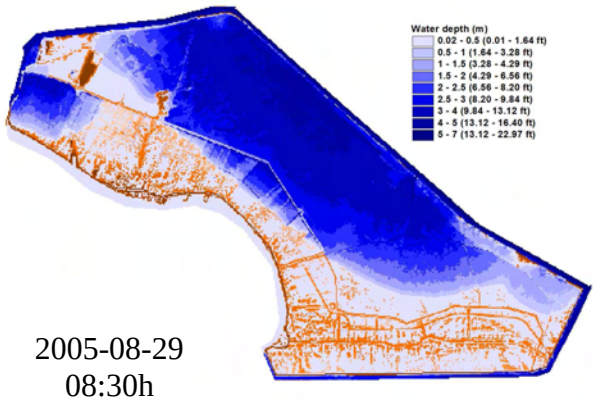
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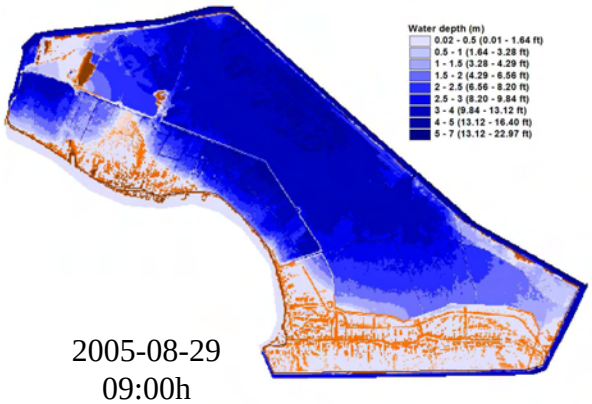
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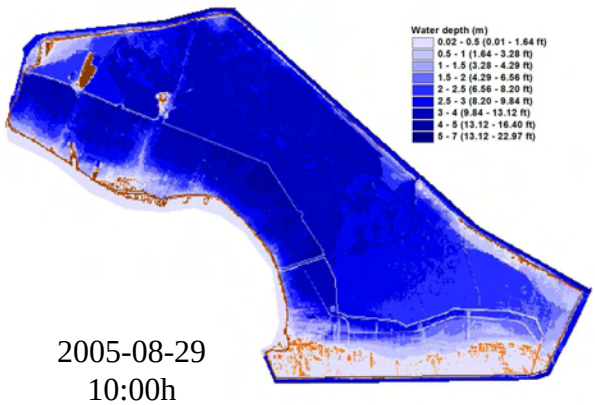
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2005-08-29
10:00h

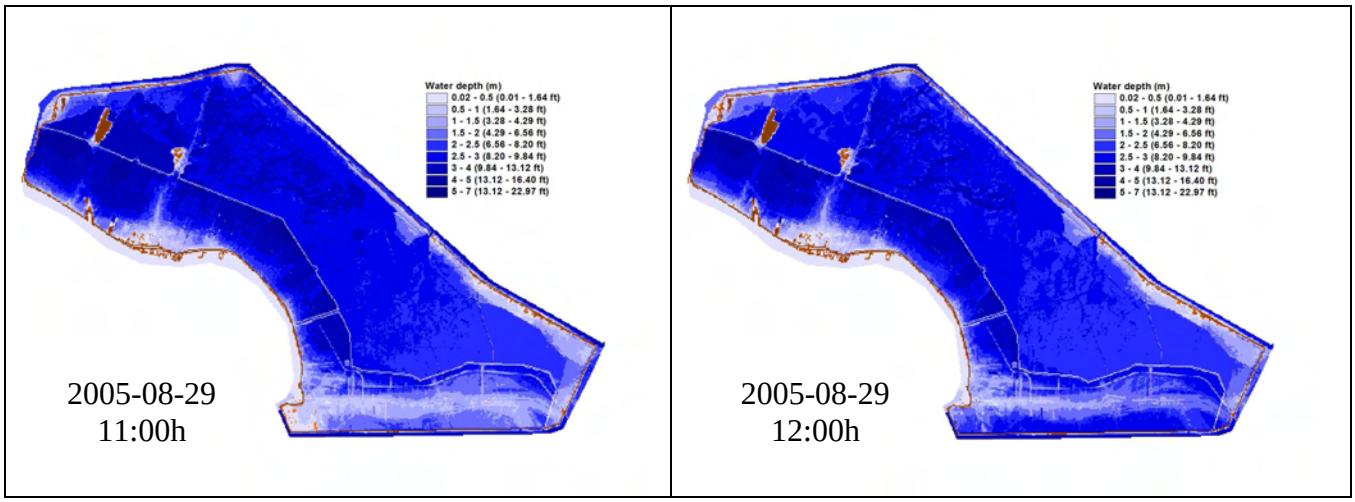


Figure 5.2 Progressing snapshots of the computed internal flooding water depth inside the St. Bernard bowl

Figure 5.2 shows the calculated maximum internal flooding depths in the St. Bernard bowl as a consequence of the breaches and overtopping initiated by hurricane Katrina. Figure 5.4 shows the comparison between our computed internal flood hydrographs and those presented by IPET for the St. Bernard bowl. The locations of the hydrographs are indicated in figure 5.1, location A corresponds with Lower 9th Ward NW., B with Lower 9th Ward E. and C with Chalmette. IPET based its hydrographs on eye witness accounts, stopped clock times and time/date stamped digital photographs. Our computed flood hydrographs are very similar to the data presented by IPET. The predicted peak flood level is within a foot of IPET's measurements. The peak in the model is a couple of hours earlier and the water level starts to decrease earlier than in the IPET hydrographs. The final water descent rate in the model is about equal to the IPET hydrograph.

As discussed previously, in extreme events such as Katrina is difficult if not impossible to get direct measurement of some input data such as water levels at the time of a breach, especially right at the breach location. However, the differences between the computer model results and the calibration data are fully acceptable. For the purpose of this study the model results are very credible.

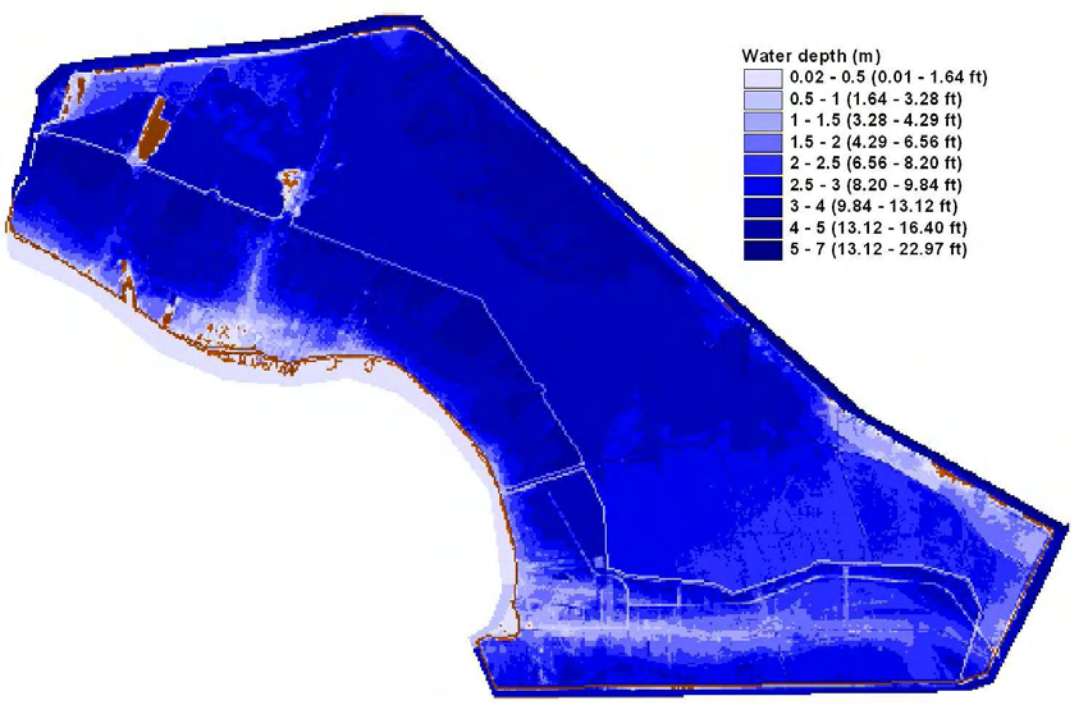


Figure 5.3 Maximum computed internal flood depths, St. Bernard bowl, as a consequence of hurricane Katrina and the numerous levee failures.

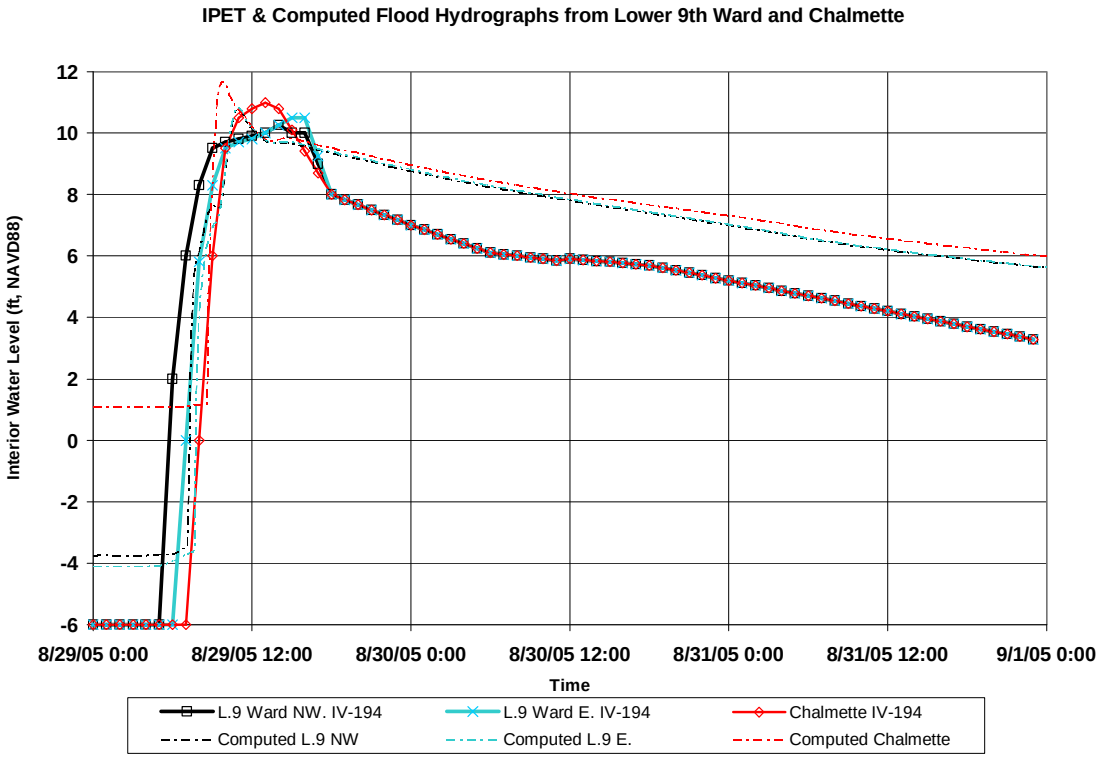


Figure 5.4 Comparison of our computed internal flood hydrographs and that presented by the IPET team.

5.2 What-if scenarios

In this paragraph several "what-if scenarios" for Saint Bernard will be presented. These scenarios will provide more information on the contribution to the flood by the different causes of the flood, like overtopping versus rainfall versus breaching and so on.

For the St. Bernard bowl seven different internal flooding model scenarios were developed:

1) Scenario all causes represented as the line '**All causes'**
2) Scenario without breaches (inclusive overtopping and rainfall) represented by the line or curve '**No Breaches'**
3) Scenario without breaches at MRGO (inclusive breaches at IHNC, overtopping and rainfall) represented by the curve '**No Breaches MRGO'**
4) Scenario without breaches at IHNC (inclusive breaches at MRGO, overtopping and rainfall) represented by the line '**No Breaches INHC'**
5) Scenario only overtopping (without breaches and without rainfall) represented by the curve '**Only Overtopping'**
6) Scenario only rainfall without pumps (without breaches and without overtopping) represented by the line '**Rain no pumps'**
7) Scenario only rainfall with 100% pump capacity (without breaches and without overtopping) represented by the curve '**Rain 100% pumps'**

Scenario 1 is equal to the Katrina event. Scenario 2 is the Katrina event without all the breaches whether MRGO or INHC and flooding is due to overtopping of the pre-Katrina levees/flood walls and rainfall. In scenario 3 the breaches at MRGO are left out. These breaches are the eroded MRGO levee and the two breaches at Bayou Bienvenue and Bayou Dupree. In scenario 4 the breaches at IHNC are left out, these breaches are the North and South breach at the IHNC. Scenario 5 considers only overtopping of the pre-Katrina levees/flood walls. Scenarios 6 and 7 show the upper and lower bound or limits of the flooding if there had been no breaches and no overtopping. Scenario 6 shows the water levels with only rainfall, when no water is pumped out (upper bound of the water levels due to rainfall). Scenario 7 shows the water levels with only rainfall, when all pumps in St. Bernard function at 100% of their rated pump capacity according to IPET [3]. During Katrina the pumps did not function in St. Bernard [3].

At ten locations in the bowl, indicated in figure 5.5, internal flooding water level changes have been computed for each of the 7 scenarios. The locations 1 to 6 are pair wise located along lines perpendicular to the 40-Arpent levee. The northern location of each pair has a lower surface elevation than the southern one, therefore the development in time of the flooding (water level) for each scenario is different for both locations in the same pair.

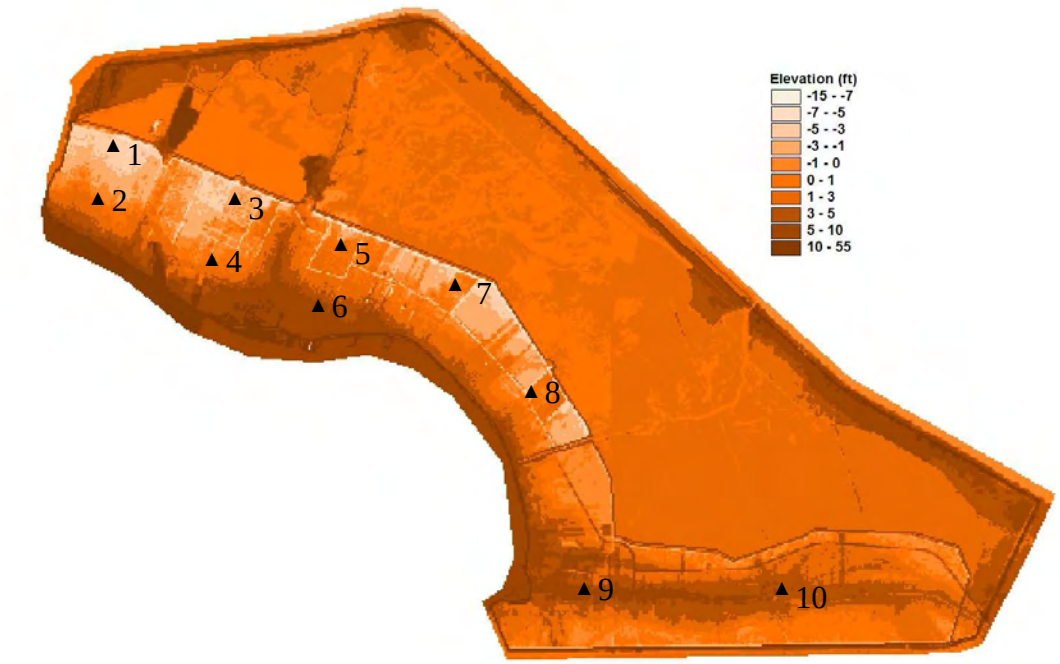


Figure 5.5 Water level locations scenario runs St. Bernard bowl.

Figures 5.6-5.15 show the changes in water levels on the ten locations. The flooding that is represented by the difference between the black solid (All Causes) and red dashed (No Breaches) line is that caused by all the breaches and levee erosion that occurred during the storm. The difference between the black (All Causes) and gray (No Breaches INHC) line is the flooding that resulted from the two big the breaches along the IHNC into the Lower Ninth ward. The contribution to the overall internal flooding resulting from the breaches of the MRGO levee are depicted by the difference between the black (All Causes) and purple dashed (NO Breaches MRGO) lines. Flooding due to rainfall, such a there is, is depicted by the difference between the green dashed-dot line (Only Overtopping) and the red dashed line (No Breaches).

The model results depicted in Figures 5.6 to 5.15 clearly show the real importance of elevation in this polder in relation to the depth of flooding. Rainfall for example flows into the lower lying areas, and the higher lying locations hardly show any flood level increase with the two scenarios (scenario 6 and 7) that only consider rain. In the under bound approach (scenario 7 - only rain with 100% pump capacity) only the relatively low lying locations 1 and 7 show a small amount of rain water, being less than one foot. The upper bound approach (scenario 6 - only rain without pumps) also does not show much rainwater flooding. The scenario that considers only overtopping shows some flood water at the lower western part of the Lower 9th Ward (location 1). The overtopping from the IHNC is not enough to fill more of the St. Bernard bowl beyond the Lower Ninth ward.

The overtopping of the MRGO levee is not enough to fill the Wetlands basin between MRGO and 40-Arpent levee up to the crest elevation of the 40-Arpent levee. This is significant as the model shows that if the structures along the INHC and MRGO had not breached, there would have been limited flooding in the St Bernard bowl.

Therefore the main causes for the flooding of the populated area inside the St. Bernard bowl are the breaches in the IHNC and MRGO.

An interesting observation is that without the IHNC breaches almost the same volume of flood water enters the populated area of the St. Bernard bowl compared with the scenario off MRGO breaches plus overtopping plus rain. Without the IHNC breaches it takes a little longer in the western part of the bowl to reach the peak water level, but the peak itself is only marginally lower. In the eastern part of the bowl the influence of the IHNC breaches on the development of the water level is even smaller. The IHNC breaches do however influence the outflow of the water out of the Lower 9th Ward and Chalmette. Floodwater 'leaked' out of the bowl through the INHC breaches for many days after the storm had passed. Without these breaches the flood water can only flow over the 40-Arpent levee into the wetlands, therefore after the peak the flood water level decreases slower without the IHNC breaches.

On the other hand, the scenario with only the IHNC breaches, overtopping and rainfall (without MRGO breaches), reveals that the St. Bernard bowl still suffers significant flooding although flood depths are significantly less than the scenario that includes the MRGO breaches.

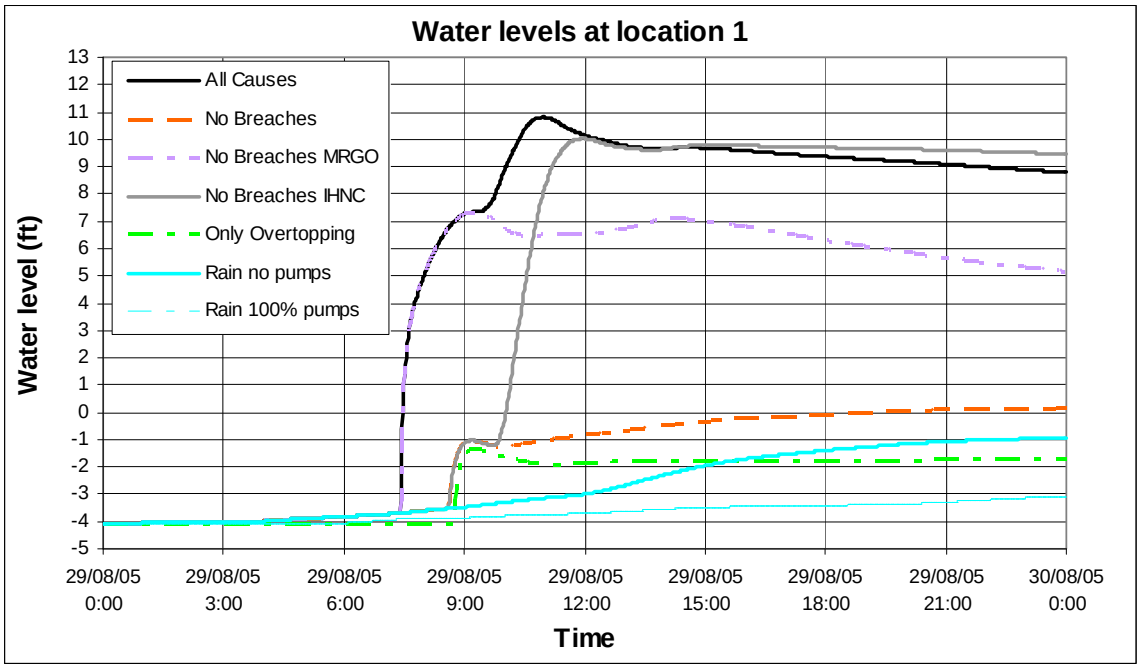


Figure 5.6 Water levels location 1 St. Bernard

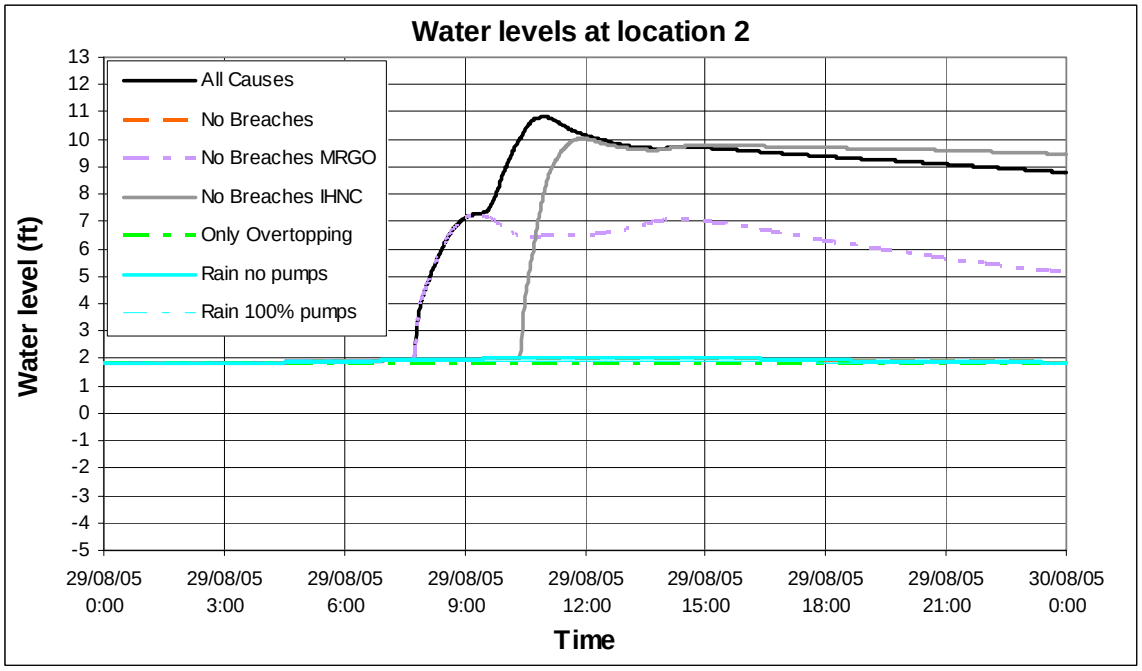


Figure 5.7 Water levels location 2 St. Bernard, the red, green and 2 blue lines are lying (almost) under each other

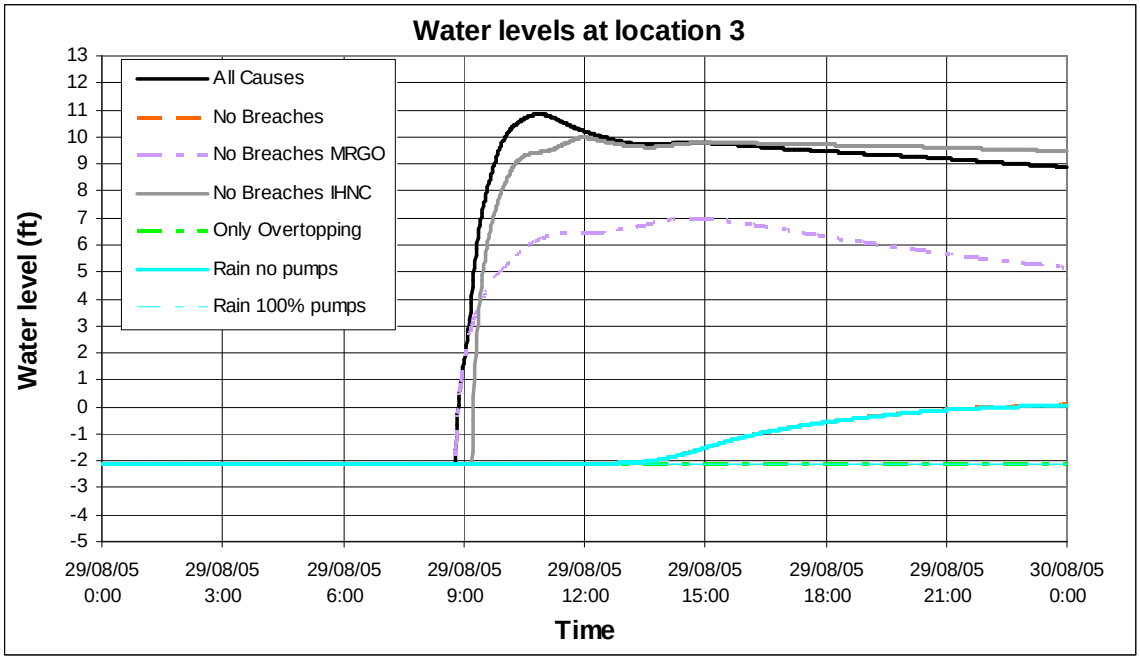


Figure 5.8 Water levels location 3 St. Bernard, the red line lies under the solid blue line, the dashed blue line lies under the dashed blue line

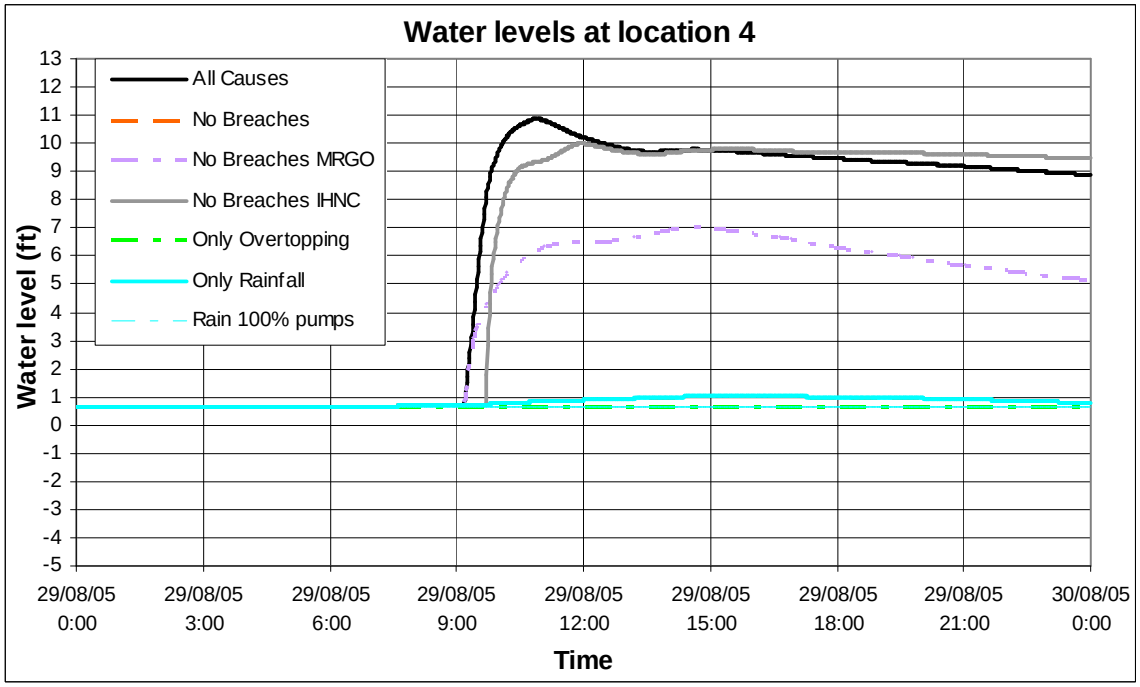


Figure 5.9 Water levels location 4 St. Bernard, the red line lies under the solid blue line, the dashed blue line lies under the dashed green line

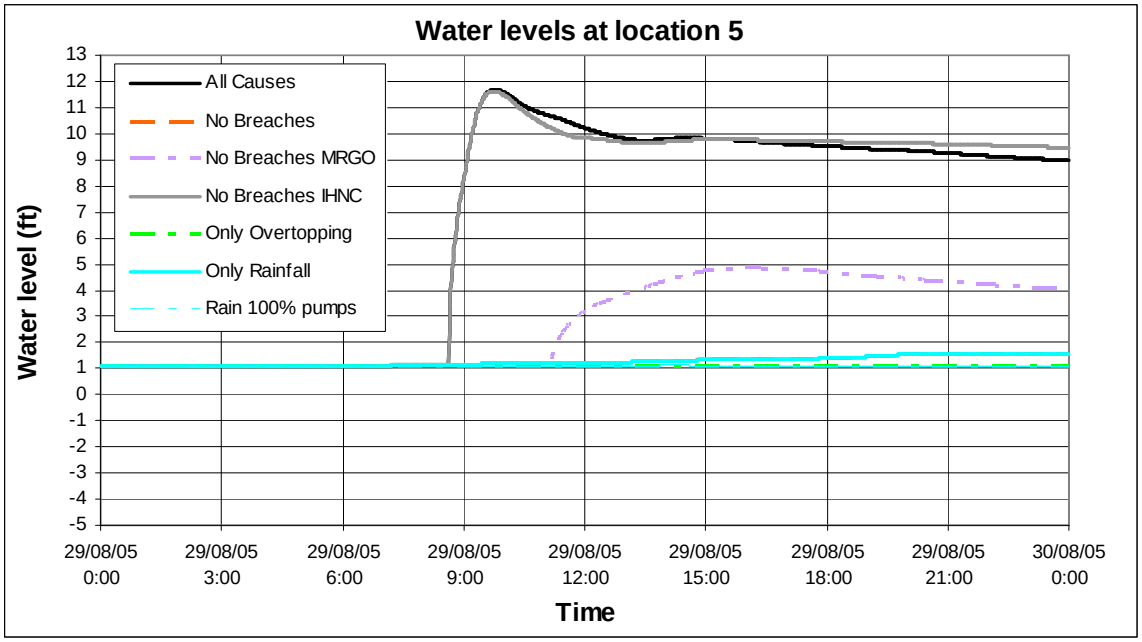


Figure 5.10 Water levels location 5 St. Bernard, the red line lies under the solid blue line, the dashed blue line lies under the dashed green line

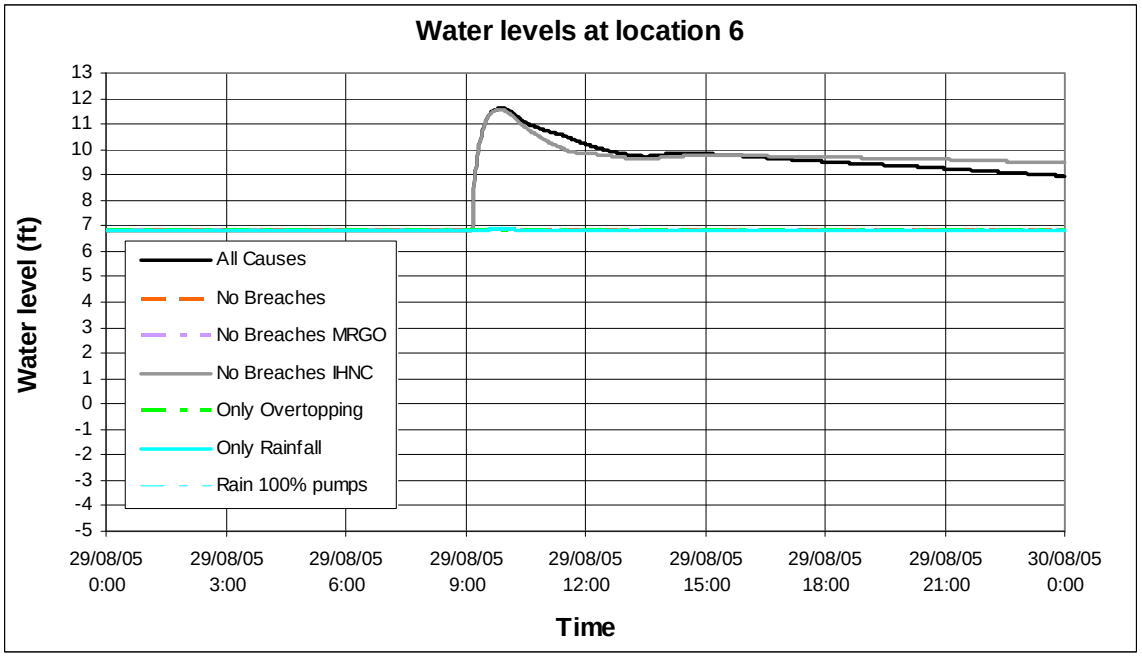


Figure 5.11 Water levels location 6 St. Bernard, the red, purple, green and blue dashed lines lie under the blue line.

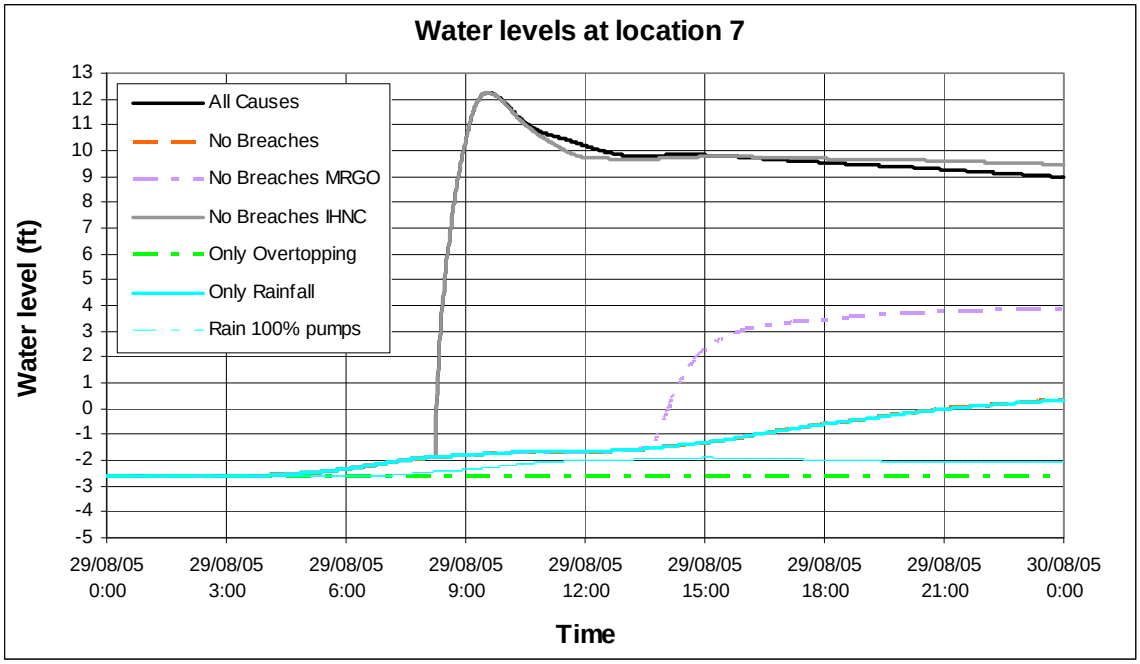


Figure 5.12 Water levels location 7 St. Bernard, the red line lies under the solid blue line.

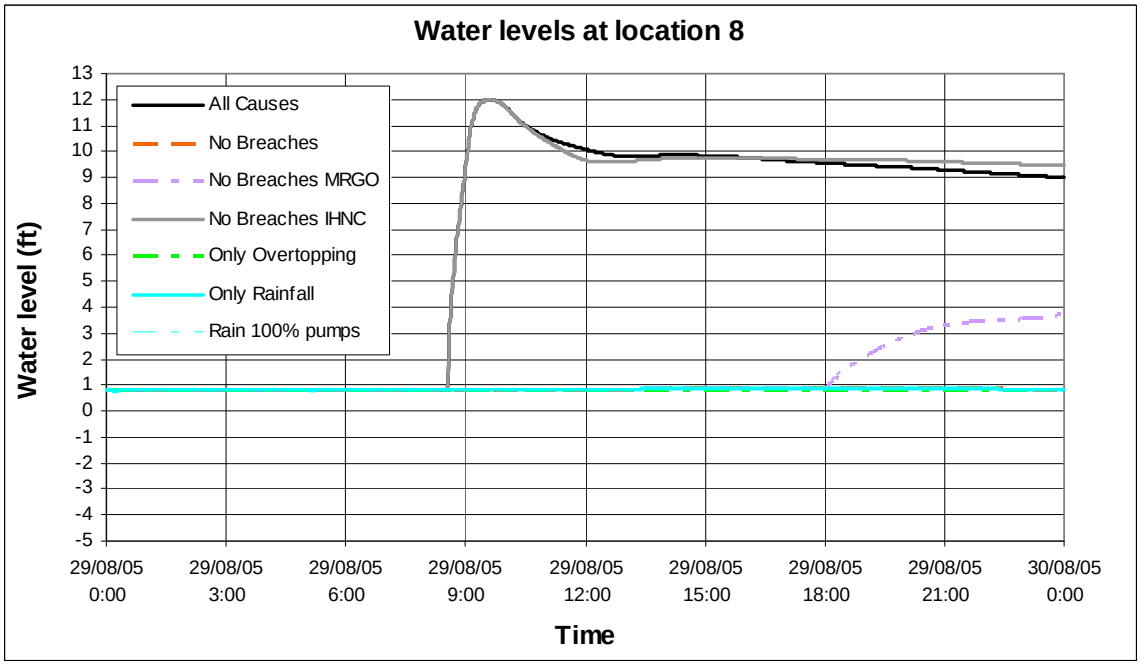


Figure 5.13 Water levels location 8 St. Bernard, the red, green and blue dashed lines lie under the blue line.

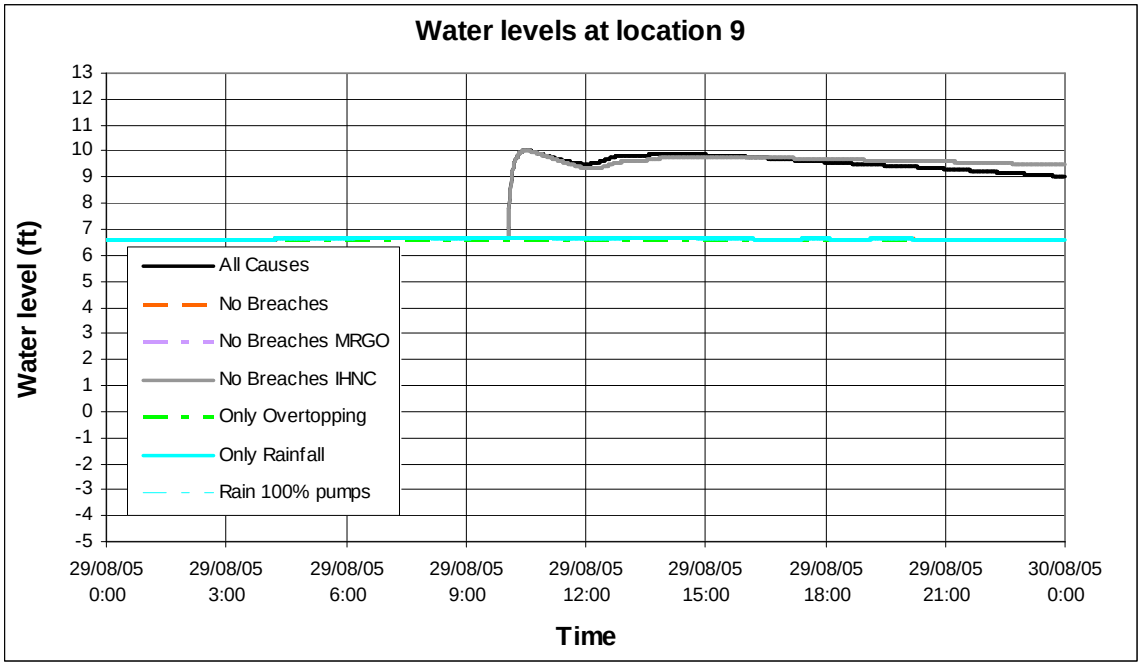


Figure 5.14 Water levels location 9 St. Bernard, the red, purple, green and blue dashed lines lie under the blue line.

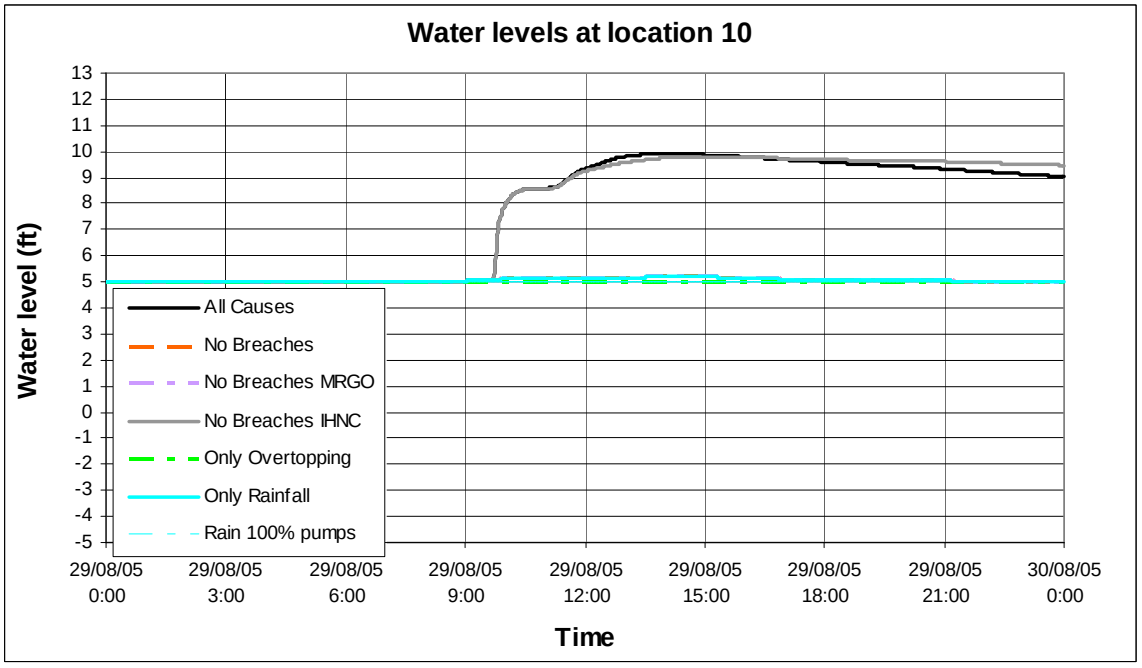


Figure 5.15 Water levels location 10 St. Bernard, the red, purple, green and blue dashed lines lie under the blue line.

5 Conclusions

In this research project we built flood simulation models for the three bowls that comprise Greater New Orleans. With this model, the Katrina flood in August 2007 has been simulated, and we obtained good agreement between the model output and the eye witness reports.

The model is used to assess the following causes of the flooding: rainfall (and the use of the pumping stations), overtopping of the levees and flood control structures, and the breaches. It is concluded that the contribution of these sources depend on the location, and the results are shown for a number of locations. It can be concluded that rainfall and overtopping contributed heavily to the flooding of Orleans East. In the bowls Orleans Metro and Saint Bernard the contribution of rainfall and overtopping is relatively small compared with the contribution of the breaches. We refer to the figures where the relative contribution of the causes is shown.

Further refinements of the modeling may be possible as additional data becomes available especially as relates to the operation of the pumps, how long they pumped for and their capacities with changing water levels both within and without the polders. The model results could aid in assess the economic damage and causes of loss of life related to the various water inputs and contributions to the internal flooding of the polders during hurricane Katrina.

6 References

[1] Link, E. et al. [IPET] (26 March 2007) Performance Evaluation of the New Orleans and SouthEast Louisiana Hurricane Protection System. Final Report of the Interagency Performance Evaluation Task Force. Volume IV - The Storm

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[3] Link, E. et al. [IPET] (26 March 2007) Performance Evaluation of the New Orleans and SouthEast Louisiana Hurricane Protection System. Final Report of the Interagency Performance Evaluation Task Force. Volume VI - The Performance - Interior Drainage and Pumping

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