Reconciling New Orleans Pumping Data with Gauge Observations of Isolated Extreme Rainfall Due to Hurricane Isaac

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ABSTRACT

Slow-moving Hurricane Isaac affected the northern gulf coast between August 28th and August 31st, 2012. Previous studies of the event reported on the hydrometeorology of the event across southeast Louisiana and southern Mississippi (Lincoln, et al., 2013). This report provides an in-depth examination and analysis of a suspected rainfall extreme in the New Orleans, Louisiana metropolitan area. Event analysis for most natural watersheds involves examination of river discharge data and the modeling of infiltration to infer watershed-average rainfall. New Orleans is unique because its topography does not allow for runoff and rainfall must be pumped out of the city. A methodology is proposed which uses data from pumping records as a proxy for streamflow out of the New Orleans "watershed." A hydrologic model was created estimate runoff by modeling infiltration using the Green & Ampt method. Modeled runoff was compared to runoff inferred from pumping records to validate rainfall estimates. Modeled runoff was within 1% of the runoff inferred from pumping records; this strongly suggests that a relatively extreme amount of rain – exceeding the 1% annual event – did occur over parts of New Orleans during Hurricane Isaac.

1. Introduction

In "2012 Southeast Louisiana and Southern Mississippi Flooding Due to Hurricane Isaac" (Lincoln, et al., 2013), preliminary data was presented for an isolated area of extreme rainfall (greater than 20 inches) that occurred across a portion of the New Orleans metropolitan area. Since the writing of that report, additional data was obtained and analyzed by hydrologists at the National Weather Service (NWS) Lower Mississippi River Forecast Center (LMRFC). Additional data included pumping records from the Sewerage and Water Board of New Orleans (SWBNO). Some additional quality control work was also done to rain gauge data in the New Orleans vicinity. This report is intended to supersede some data and conclusions regarding local rainfall amounts in New Orleans found in Lincoln, et al. (2013), and is believed to be the most comprehensive review of the local rainfall event currently available.

The following discussions consist of four subtopics: 1) The hydrology of New Orleans and Hurricane Isaac's impact; 2) estimating pumped flow rates; 3) further quality-control of precipitation estimates (beyond that of Lincoln, et al (2013)) and modeling rainfall/runoff relationships in portions of New Orleans during Isaac using a hydrologic model; and 4) the results of our modeling analysis and comparing the results to observations.

1a. New Orleans Hydrology

Most natural watersheds are defined by an outlet location that is typically the lowest elevation in the watershed and ridges that separate the direction of overland flow toward the outlet (Figure 1). Rainfall occurring in the typical watershed flows downhill from the higher elevations into streams, and these streams then carry water to the outlet point where it leaves the watershed. The city of New Orleans presents a unique hydrologic situation. New Orleans, in contrast, is completely surrounded by higher terrain and rainfall would thus have a natural tendency to collect in the lowest sections of the city unless otherwise removed by evapotranspiration or pumping. A further complication is the fact that most of New Orleans proper - about 65% - is at or below mean sea level (Figure 2), as defined by the average elevation of Lake Pontchartrain during the 1983-2001 period, estimated at about 0.4 ft NAVD88.

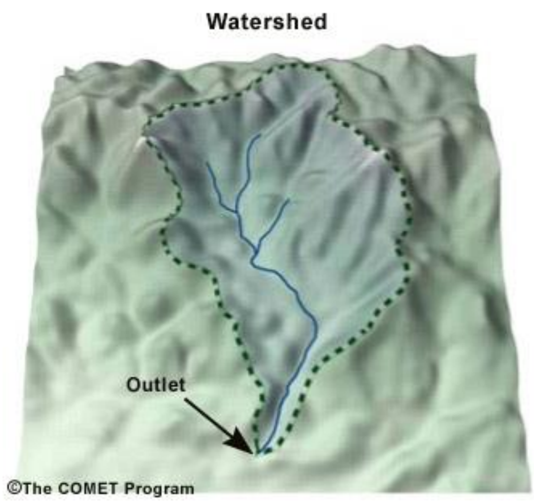


Figure 1. A hypothetical watershed, as defined by the outlet point.

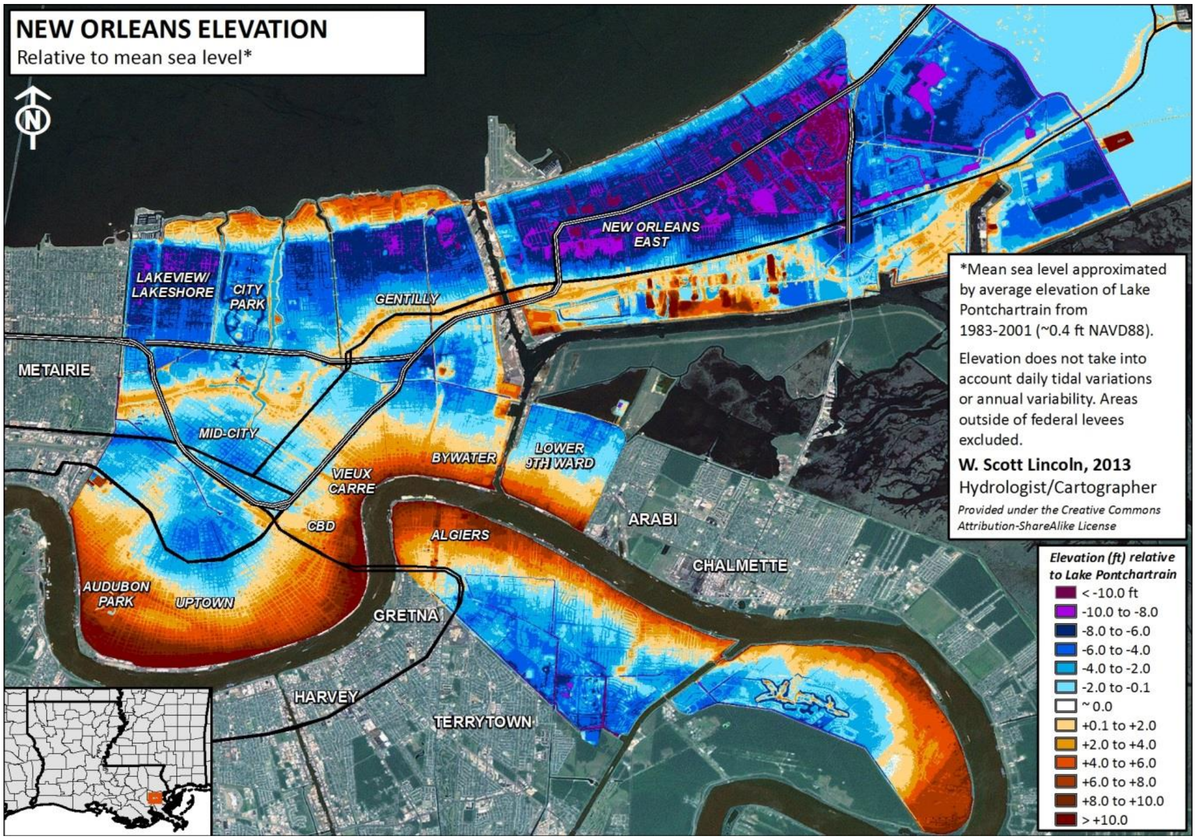


Figure 2. Elevation map of New Orleans excluding suburbs and areas outside of the federal levee system. Elevation is relative to mean sea level, as defined by Lake Pontchartrain average level from 1983-2001.

To facilitate drainage of stormwater out of New Orleans, the SWBNO operates 23 pumping stations within the city, which contain 113 total pumps (Interagency Performance Evaluation Task Force, 2006). At a typical pumping station, storm water is either pumped from the underground storm sewer network into an outfall canal, or pumped from an outfall canal to Lake Pontchartrain. Since Hurricane Katrina, closure gates have been added to the outfall canals to prevent water in Lake Pontchartrain or Lake Borgne from entering the interior drainage system. Because of this, the United States Army Corps of Engineers (USACE) also operates some pumping stations to move water from the interior drainage network out of the city.

1b. Hurricane Isaac's effect on New Orleans

As mentioned in "Appendix C" of Lincoln et al. (2013), an isolated area of very heavy rainfall was observed in a small section of New Orleans (Figure 3). Two storm total rainfall observations of over 20.0 inches in the Audubon Park vicinity of New Orleans were originally considered questionable by NWS forecasters due to the lack of corroborating gauges nearby and the lack of flooding reports in the area (anecdotally, "that much rain always causes flooding"). Additional rainfall data was obtained after the storm, including rainfall from CoCoRaHS gauges and from private weather stations. NWS forecasters also visited a few of these private gauges to gather more information about potential sources of uncertainty. With five (5) gauges reporting similar rainfall rates and rainfall accumulations near the Mississippi River – both in New Orleans and close suburbs - Lincoln, et al. (2013) concluded that the questionable rainfall reports were likely validated. It was also suggested that to further verify the rainfall amounts, pumping records from the SWBNO could be evaluated because the pumped volume of water versus time could serve as a proxy for streamflow measurement associated with a typical watershed. Here we present findings from these additional efforts to verify the rainfall amounts in New Orleans.

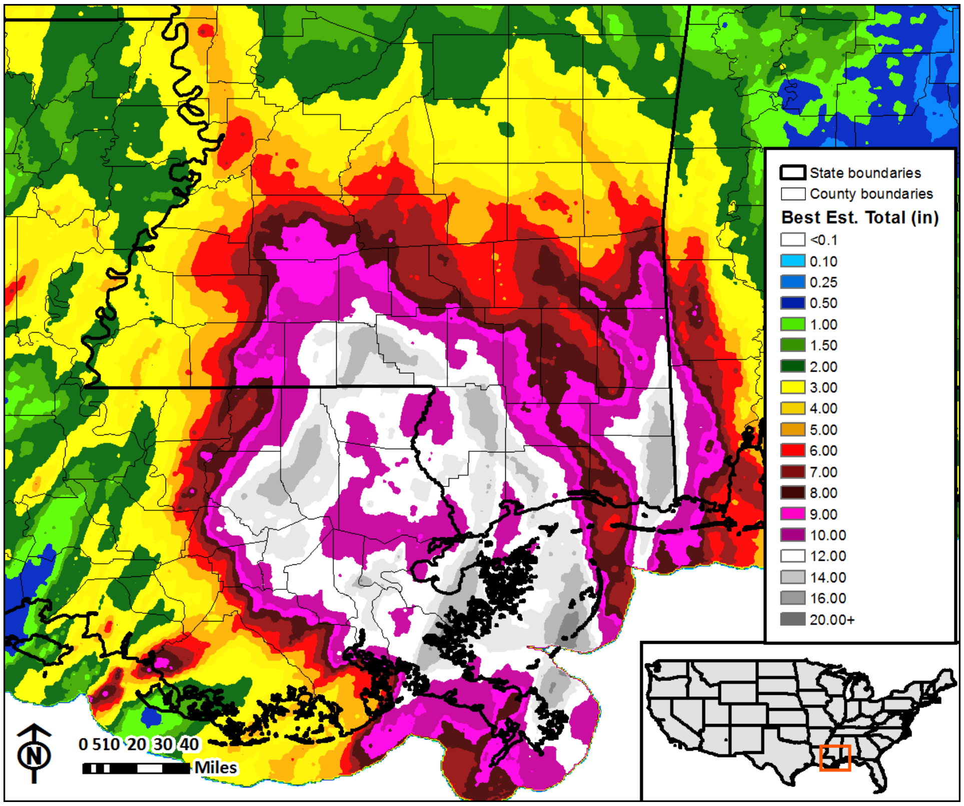


Figure 3. Hurricane Isaac storm total rainfall as estimated by a combination of official gauges, radar data, and forecaster experience in the NWS RFC Best-Estimate product. Note swaths of higher rainfall in coastal Mississippi and southeast Louisiana, including the small, isolated maxima in the New Orleans area. Figure from Lincoln et al. (2013).

2. Methodology

For natural watersheds, hydrologists can estimate the average runoff that occurred in the watershed using stream observations at the outlet point. If a relationship between stream depth and stream flow exists (called a rating curve), the total volume of water leaving a watershed during an event can be estimated from the hydrograph (Figure 4). First, the baseflow contribution is removed from the streamflow hydrograph. Then the rate of water leaving the watershed at each timestep is summed and divided by the contributing area. The result is the equivalent uniform depth (EDU), or average watershed runoff. The runoff can be described as the portion of the rainfall that did not infiltrate into the soil, become intercepted by vegetation, become trapped in detention areas, or evaporate. Thus, the runoff is a good estimate for the minimum possible rainfall amount averaged across the watershed. Additional modeling techniques can be used to estimate the total rainfall and total infiltration once the runoff is known.

As mentioned earlier, the city of New Orleans does not behave like a typical watershed. Because all rain that falls on the city of New Orleans must be pumped out, the volume of runoff that occurred during an event could be approximated if the volume of water pumped is known or can be reasonably estimated, similar to using the event runoff portion of a hydrograph in a typical stream. A hypothetical hydrograph for the city of New Orleans would also differ from that of a typical stream because the urban landscape would cause more rainfall to immediately runoff to drainage canals and the storm sewer network due to impervious surfaces. This would have the effect of greatly reducing the baseflow contribution, but increasing the runoff contribution, making the hydrograph peak higher and quicker (Figure 5).

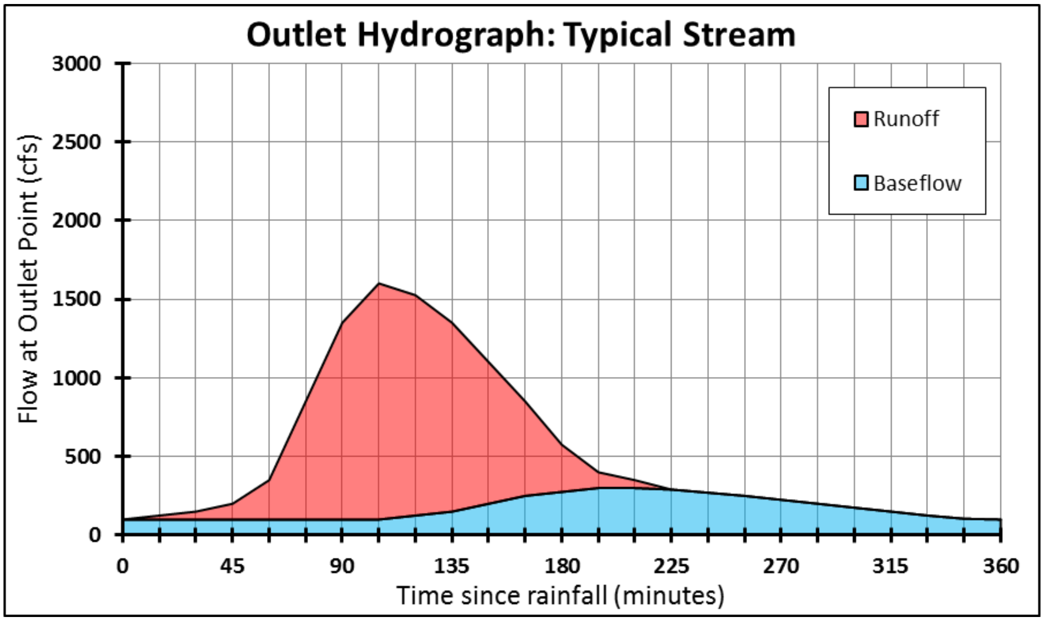


Figure 4. A hypothetical hydrograph for a typical stream's watershed outlet point. Baseflow is the contribution from water stored in the soil below the water table that slowly moves toward streams in the watershed. Runoff is the direct contribution from rainfall that does not infiltrate into the soil but instead runs over the land surface to streams and then to the outlet point. Hydrologists can estimate the average runoff that occurred in a watershed by removing the baseflow contribution and integrating the remaining volume under the hydrograph.

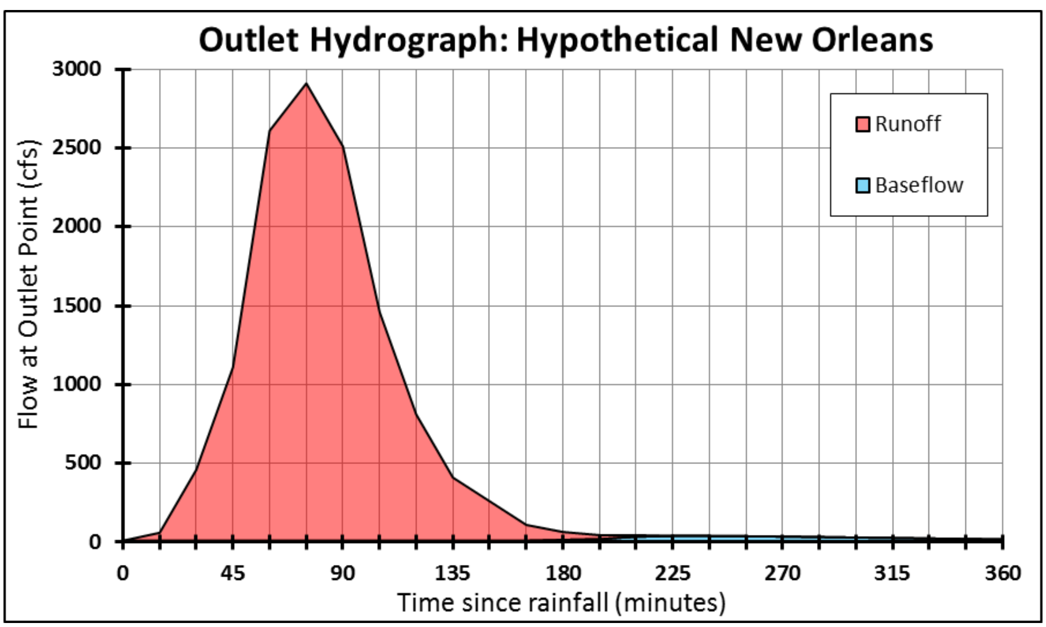


Figure 5. A hypothetical hydrograph for the city of New Orleans' watershed "outlet point." Similar to Figure 4, but the urban landscape will cause much less baseflow and quicker, increased runoff, even for the same amount of rainfall.

2a. Digitization of SWBNO pumping records

The city of New Orleans can be broken up into five main areas that need to be pumped during rainfall, separated by the Mississippi River, the Inner Harbor Navigation Canal (IHNC), and the Intracoastal Waterway (ICWW). This creates five main polders, or artificial watersheds, within the city, which we have labeled as Main, East, Lower 9th, Algiers, and English Turn (Figure 6). The storm drainage network is independent in each of these areas. To verify rainfall that occurred in the uptown areas of New Orleans, we would only need to estimate the amount of water pumped out of the "Main" polder of the city. This section of the city includes several pumping stations operated by SWBNO: drainage pumping station 1, 2, 3, 4, 6, 7, 12, and 19. Drainage pumping stations 1, 2, and 3 pump from one interior canal to another interior canal, and drainage pumping stations 4, 6, 7, 12, and 19 pump from an interior canal to an outfall canal. Therefore, data from pumping stations 4, 6, 7, 12, and 19 are aggregated to estimate the volume of water pumped out of the city.

Hydrologists from the NWS LMRFC contacted SWBNO staff during summer 2013 to request pumping records for New Orleans. SWBNO staff compiled records for the August 26th through August 31st period for stations within the "Main" polder. Records of tailwater, headwater, and whether or not a pump was operating are written on paper log sheets by hand at hourly or half-hourly intervals; an example is illustrated by Figure 7. Hydrologists visited SWBNO offices in September 2013, scanned in over 100 pages of records, and then digitized the records into a spreadsheet. Pumping records from station 12 were not available, however the contributing area to this station was only about 6% of the study area, and was also not impacted by the heaviest rainfall amounts. To accurately estimate the rate of water being pumped by a single pump, the tailwater/headwater elevation difference (static head) is required, as well as relationship between static head and flow rate, which is unique to each pump size and type.

After Hurricane Katrina flooded large sections of New Orleans, numerous pump stations were damaged. An Interagency Performance Evaluation Task Force (IPET) was assembled to document the performance of the hurricane protection system in the New Orleans area. In Volume IV of their report, IPET documented the status of the pumping stations and the repairs needed to bring stations back to capacity (Interagency Performance Evaluation Task Force, 2006). IPET also created pump curves (plots showing the static head relationship with flow rate) for almost all pumps controlled by SWBNO. Pump curves for 51 different pumps presented in the IPET (2006) report were digitized into a spreadsheet format that could be easily referenced by the pumping records.

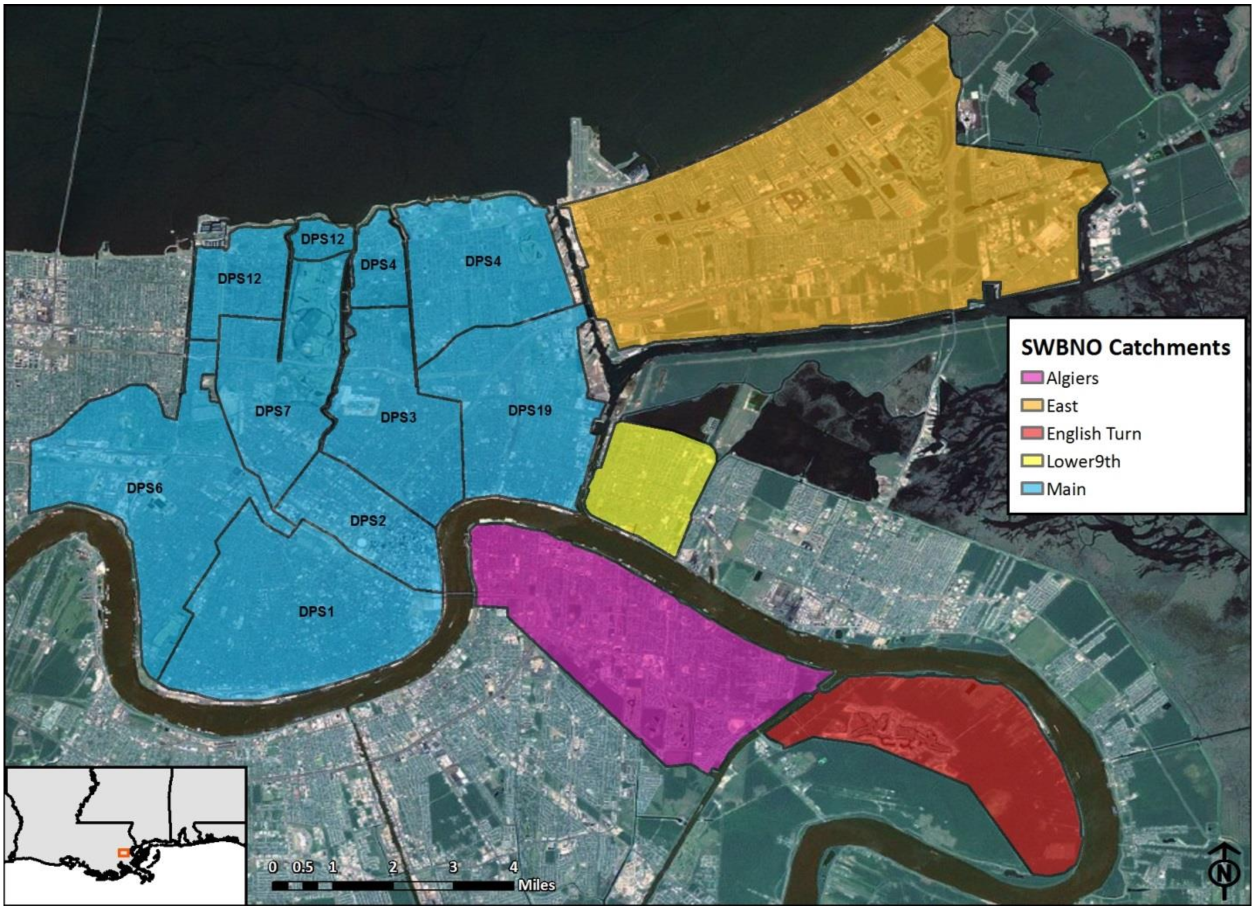


Figure 6. Polders of the New Orleans storm drainage network. The creation of levees to protect the city of New Orleans from flooding had the side effect of creating several completely-enclosed, artificial drainage catchments (polders) which must be manually drained. Catchments within the "Main" polder defined by SWBNO pumping stations are labeled.

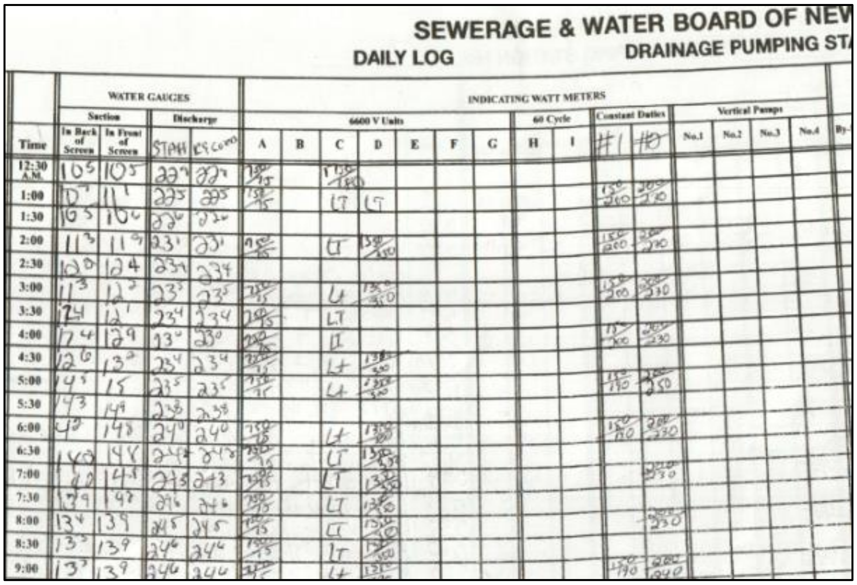
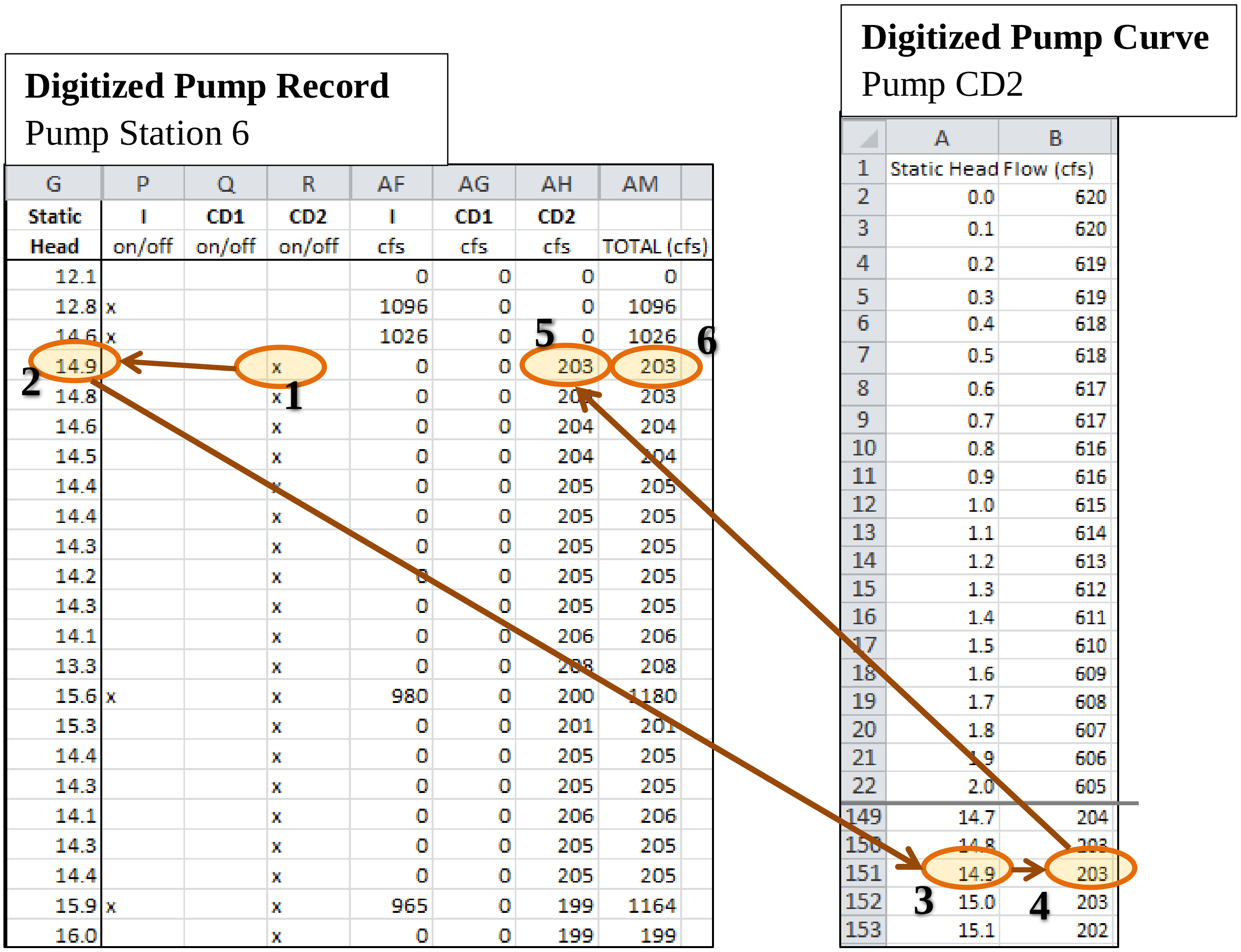


Figure 7. Example section of a daily log sheet for a pump station operated by SWBNO.

2b. Calculation of runoff from pumping records

Flow pumped by a given pump station was estimated using two different spreadsheets – one a digitized database of pumping records from Isaac, and another containing a look-up table derived from digitized pump curves. For a given timestep and pump, if the pump was in operation, the observed static head was converted to a flow in cubic feet per second (cfs) based upon the pump curve lookup table, as illustrated by Figure 8. This process was repeated for each pump in a given pump station for each timestep (either hourly or half-hourly). The pumped flow rate for each pump was summed by timestep, and then a total pumped volume was calculated. Dividing the total pumped volume by the contributing area produces EUD, or average runoff depth.



Digitized Pump Record
Pump Station 6

G	P	Q	R	AF	AG	AH	AM
Static Head	**I** on/off	**CD1** on/off	**CD2** on/off	**I** cfs	**CD1** cfs	**CD2** cfs	TOTAL (cfs)
12.1				0	0	0	0
12.8	x			1096	0	0	1096
14.6	x			1026	0	0	1026
14.9			x	0	0	203	203
14.8			x	0	0	203	203
14.6			x	0	0	204	204
14.5			x	0	0	204	204
14.4			x	0	0	205	205
14.4			x	0	0	205	205
14.3			x	0	0	205	205
14.2			x	0	0	205	205
14.3			x	0	0	205	205
14.1			x	0	0	206	206
13.3			x	0	0	208	208
15.6	x		x	980	0	200	1180
15.3			x	0	0	201	201
14.4			x	0	0	205	205
14.3			x	0	0	205	205
14.1			x	0	0	206	206
14.3			x	0	0	205	205
14.4			x	0	0	205	205
15.9	x		x	965	0	199	1164
16.0			x	0	0	199	199

Digitized Pump Curve
Pump CD2

	A	B
1	Static Head	Flow (cfs)
2	0.0	620
3	0.1	620
4	0.2	619
5	0.3	619
6	0.4	618
7	0.5	618
8	0.6	617
9	0.7	617
10	0.8	616
11	0.9	616
12	1.0	615
13	1.1	614
14	1.2	613
15	1.3	612
16	1.4	611
17	1.5	610
18	1.6	609
19	1.7	608
20	1.8	607
21	1.9	606
22	2.0	605
149	14.7	204
150	14.8	203
151	14.9	203
152	15.0	203
153	15.1	202

Figure 8. Flow chart illustrating the estimation of flow from an individual pump at an individual pumping station. The spreadsheet first checks to see if pump is operating (1), if it is not, flow is set to 0 cfs. If the pump is operating, the static head (2) is compared to a lookup table in the digitized pump curve spreadsheet (3) and the corresponding flow (4) is set in the pump record spreadsheet (5) for use in estimating the total flow from each pump for the that timestep (6).

2c. Mitigating sources of uncertainty in pumping records

There are a few concerns with taking the derived flow values from available pumping records that need to be addressed before the data should be used in an analysis.

1. SWBNO was running some pumps off and on for at least two days prior to the first waves of rainfall impacting New Orleans. This is partly due to attempts to lower interior drainage canals to increase storage capacity of the drainage system.

2. Although water elevations in the interior drainage canals were fairly constant at times before the onset of rainfall, each canal showed a rising trend after pumping ended prior to the onset of rainfall. This is thought to be due to water in the drainage system from past rain events being able to drain into to the canals after lowering, somewhat similar to baseflow in normal watersheds.

3. Available SWBNO pumping records ended at 12:00AM CDT September 1st, 2012 but pumping was still ongoing and likely continued after our records ended.

To address these concerns, some assumptions and corrections were needed. How we chose to address each issue, specifically:

1. **Pumps running off and on prior to Isaac landfall**

   As mentioned, some pumping prior to landfall of Isaac was likely due to attempts to increase the capacity of the interior drainage canals prior to heavy rainfall, but some may also have been in response to previous rainfall events (August 23rd and August 24th). Because of the inherent lag in a storm drainage system, it would be almost impossible to directly apportion the volume of water from events occurring within a few days of one another. For the purposes of our analysis, we decided that the pumping related to a pre-storm drawdown would have been most likely to occur when forecast tracks for Hurricane Isaac first showed a landfall near southeast Louisiana. As illustrated by Figure 9, track forecasts from the National Hurricane Center were quickly moving westward from a Florida panhandle landfall toward the New Orleans area by late on August 26th, and fixated on southeast Louisiana by the morning of August 27th. Thus, we chose 11UTC, August 27th, as the cutoff point; water pumped after to this time was attributed to a canal drawdown for Isaac.

2. **Canal elevations rising after drawdown during periods of no rainfall**

It would be almost impossible to determine which sections of the storm drainage network contributed to rising canal levels after brief periods of pumping. For our analysis, we excluded water pumped to draw down the canals – and also pumped to maintain this drop in canal elevations – that occurred before the onset of rainfall, which was roughly 17UTC on August 28th. All water pumped after 17UTC on August 28th was assumed to be from Hurricane Isaac rainfall.

3. **Pumping records ending at 12:00AM CDT (5 UTC), September 1st**

It was apparent from the data that some additional pumping likely continued after the end of available records and canal elevations had not yet been lowered to pre storm levels. Although we would not necessarily expect canal elevations to return to low levels described in #2 above due to the artificial drawdown, to accurately estimate a volume of runoff from Isaac's rainfall we would need to estimate the volume of additional water that must be pumped to return the canals to that lower, pre-storm level. We estimated a crude elevation-storage relationship for each canal based upon a comparison of pumping to change in elevation during the pre-rainfall period. We acknowledge that there will be some non-trivial uncertainty involved in using this methodology, especially considering that we are unable to account for water in the subsurface drainage network still moving toward the canals.

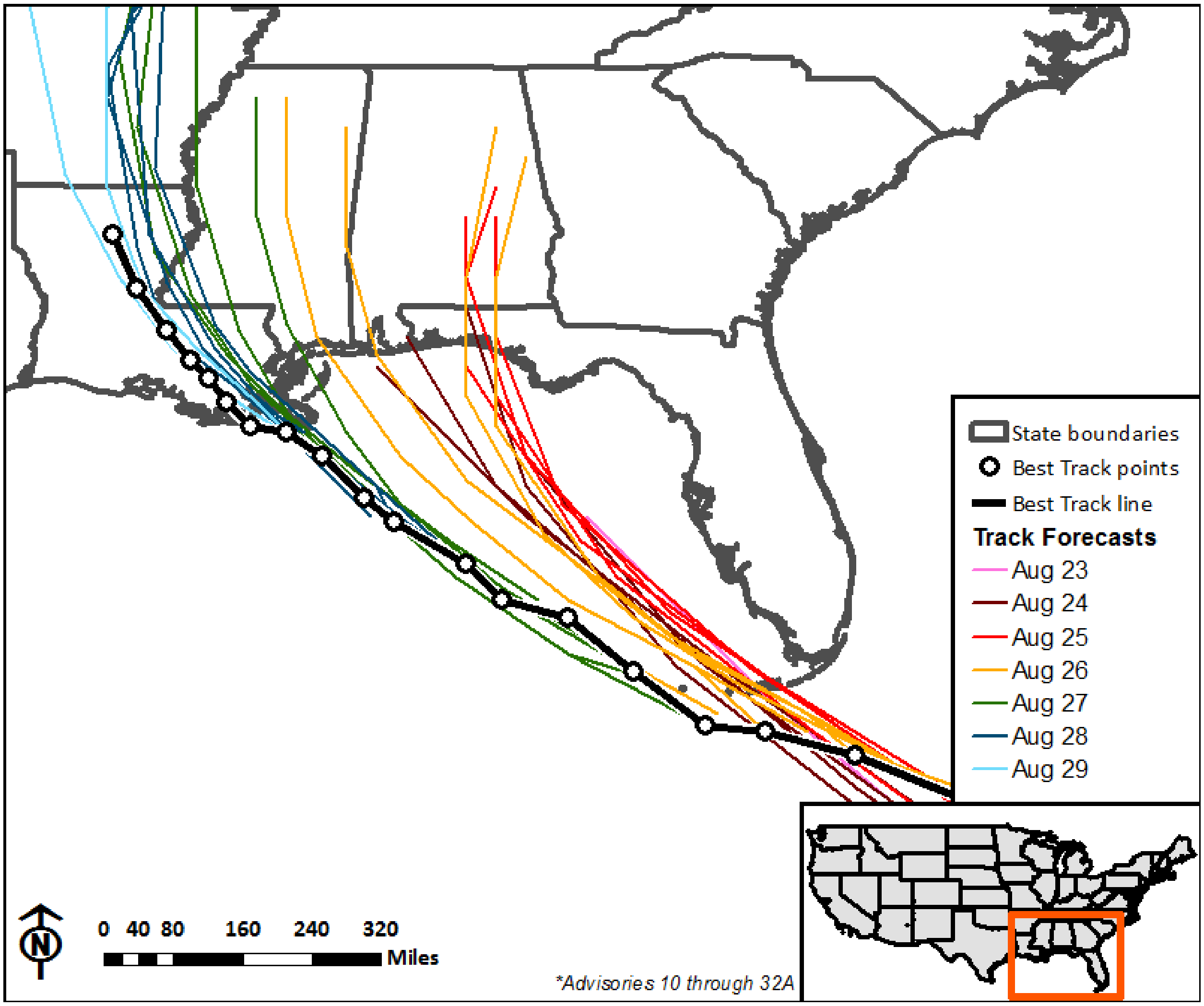


Figure 9. Five day track forecasts issued by the National Hurricane Center with the preliminary best track for Hurricane Isaac.

2d. Improving rainfall estimates

Additional quality control and analysis was done to rainfall estimates in the New Orleans area subsequent to Lincoln, et al. (2013). Some gauges had incorrect meta-data that placed them at the wrong location. Other gauges had bad reports during portions of individual days which necessitated corrections. Several gauges in the New Orleans area still likely under-estimated rainfall due to known measurement biases during windy conditions in tropical storms (Knight & Davis, 2009). The following issues were addressed to produce our final best-estimate rainfall analysis for Hurricane Isaac:

1. NWS cooperative observer (COOP) weather station NEWL1 was previously shown to be located in the center of Audubon Park, just a bit north of the other COOP station in the area, AUD. We discovered that the location of NEWL1 was incorrect; it was a second rain gauge co-located with site AUD near the Mississippi River, which we had originally treated as a separate gauge. This was also the site associated with the rainfall correction made by NWS WFO LIX staff which we previously concluded was unnecessary, so the 12.0” storm total rainfall amount was also incorrect. We removed this location from our analysis.
2. Private weather station KLABELLE5, which was originally reported as recording about 17.6” of rainfall, likely recorded higher values but the original data retrieval method did not catch an error in the Weather Underground database. The original retrieval method grabbed daily totals as reported by Weather Underground instead of manually accumulating rainfall rates. This site seemed to report accurate rainfall rates but reported the same value for total rainfall throughout August 29th even before

any rainfall. We manually accumulated rainfall rates reported by the site to correct the daily rainfall totals, which yielded a 21.7" storm total rainfall.

3. Private weather station KLANEWOR33, which was originally reported to have recorded about 27.4" of rainfall, likely reported erroneous rainfall during a several hour period on August 29th. Because this gauge was the highest known value of rainfall from the storm and had a running gauge accumulation higher than all other gauges, we gave the reading additional scrutiny. Rainfall rates for this gauge and neighboring gauges were compared to radar data at each approximately 5 minute timestep. It was found that all gauges in the area except for KLANEWOR33 matched the radar data closely; increases in rainfall intensity closely matched the passage of a heavier bands of reflectivity associated with the outer edge of Isaac's eyewall. Rainfall rates for all other gauges were plausible based upon the recorded reflectivity values and associated rain rates determined through the tropical Z-R relationship. It was also noted that there were numerous instances of very high rainfall rates on 5-10 minute timescales at the site that did not match neighboring gauges and were not associated with the passage of higher radar reflectivity through the area. One known failure mode for tipping bucket rain gauges to fail in the over-estimate direction can occur during landfalling tropical systems where strong winds cause false tips. This phenomenon seems to be poorly understood and poorly quantified in the peer-reviewed literature even though it seems to be widely known by manufacturers of this type of instrumentation. We found that the time period when rain rates at KLANEWOR33 significantly exceeded neighboring gauge locations correlated closely with the time period when frequent wind gusts above 50mph were reported.

Other time periods appeared to report plausible data consistent with neighboring gauges. Because the majority of the data reported by this station appeared to be good and helpful to understanding this rainfall event, we chose to make a correction to the questionable period of time when wind gusts exceeded 50mph. During that period, we forced the rainfall rate for KLANEWOR33 to match the average rate of neighboring gauges (NEWL1, NORL1, KLAGRETN4, and KLABELLE5). This adjustment changed the daily total rainfall for August 29th from 24.3 inches to 16.2 inches, and thus changed the storm total rainfall from 27.4 inches to 19.2 inches. We acknowledge that this adjustment brings with it considerable uncertainty due to the lack of supporting information by other rain gauge studies.

4. NWS COOP weather station TERL1, which recorded 11.0 inches of rainfall, was found to be inconsistent with neighboring gauges along the same swath. Although anecdotal information obtained for Lincoln et al. (2013) suggested that multiple COOP gauging locations besides site AUD may also have experienced failures leading to the under-reporting of storm total rainfall, this gauge was not the same type of reporting station as the sites experiencing the known issues. The equipment used by the observer is an 8 inch rain gauge manually read and reported by an observer who is considered particularly trustworthy (NWS WFO New Orleans staff, personal communication, November 2013). Because no sub-daily data was available, however, we were unable to directly compare rainfall rates from this site to the neighboring Weather Underground location with higher values. Some undercatch may have occurred due to wind effects from Isaac, but the site was not visited and the exact reasoning behind the discrepancy is not clear. The site was not excluded from

analysis but was given low weight in contour analysis when compared to neighboring locations.

After making these additional corrections to the data it became even clearer that many of the gauge readings from SWBNO were likely under-estimates of actual rainfall. We took this into consideration upon creation of best estimate rainfall analysis map (Figure 10 and Figure 11). In contrast with the earlier analysis presented in Lincoln et al. (2013), the area of highest rainfall has been reduced and many areas of rainfall below 8” have been removed. The swath of rainfall greater than 20 inches has been extended in the east-west direction to match the spatial patterns from radar estimates. The average rainfall for the Main polder changed from approximately 13.7 inches to 13.5 inches after adjustments were made. It was also noted that rainfall gauges located in the heaviest swath of rainfall had different timing and magnitude characteristics when compared to rainfall that occurred closer to Lake Pontchartrain (Figure 12, Figure 13, Figure 14).

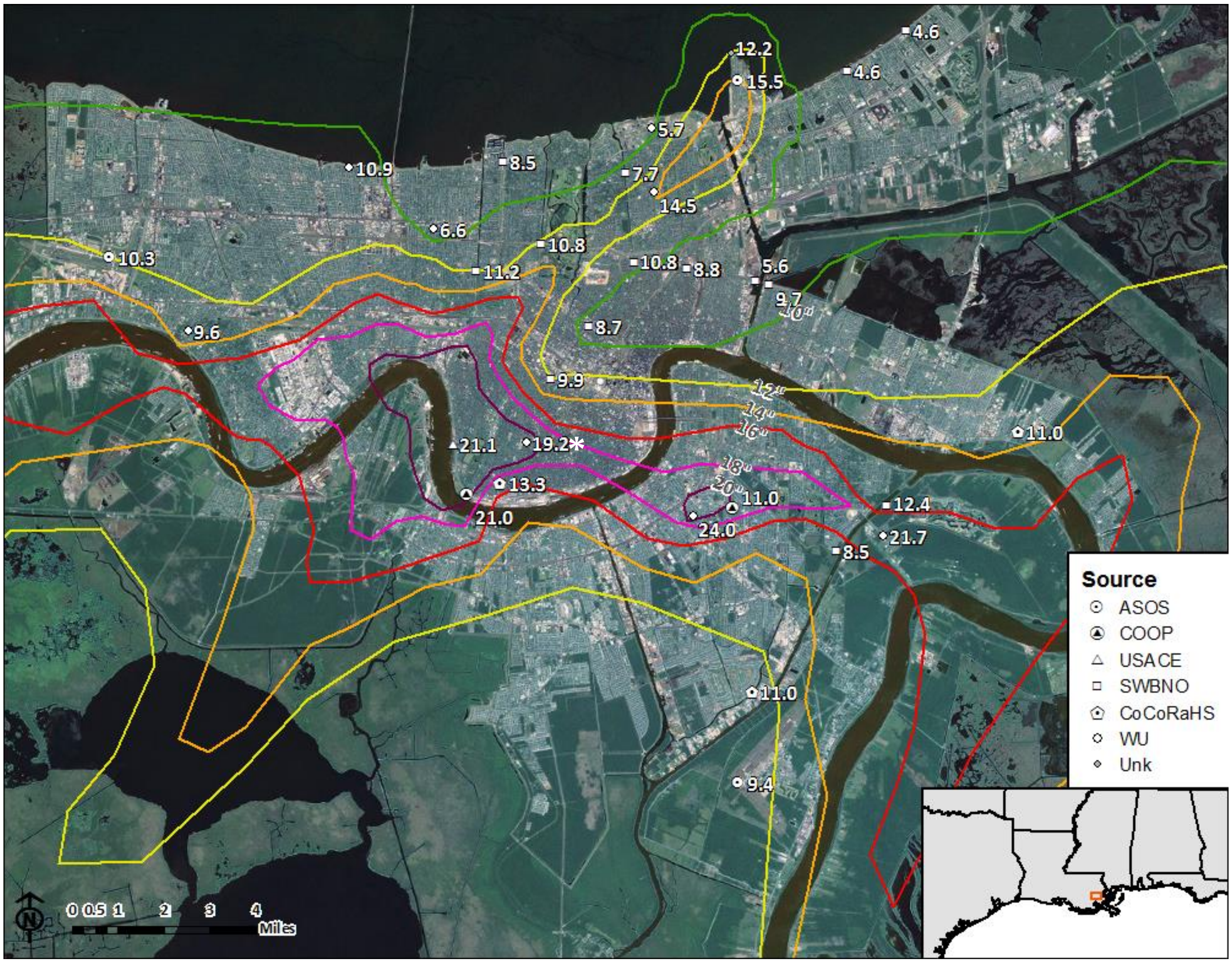


Figure 10. Storm total rainfall analyzed from official and private gauges in the New Orleans area during Hurricane Isaac. Contours were produced from a Kriging interpolation of gauges, then manually quality controlled to match spatial patterns from radar data and to take into account likely gauge under-estimates. The value for site KLANEWOR33 (19.2 in) is an estimate; see discussion for more information.

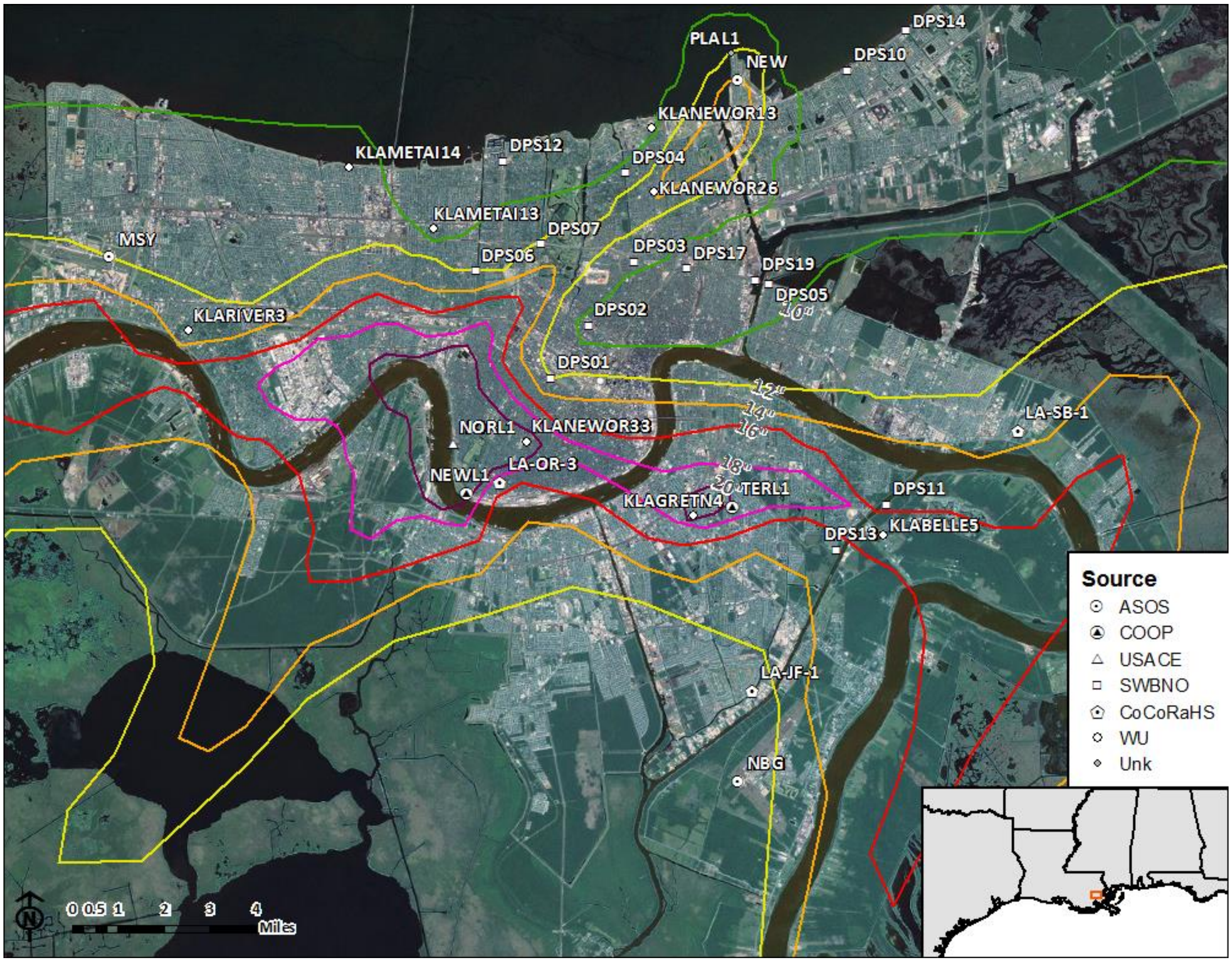


Figure 11. Same as Figure 10 but with site identifiers instead of point totals. Sites with four characters and a number are sites that come in through the HADS network and have an identifier set by local NWS WFOs. Sites with three characters are ASOS/AWOS airport stations. Sites starting with "DPS" are SWBNO pumping stations. Sites with eight characters and two numbers are Weather Underground PWS sites. Sites starting with "LA" followed by two additional characters and a number are CoCoRaHS sites.

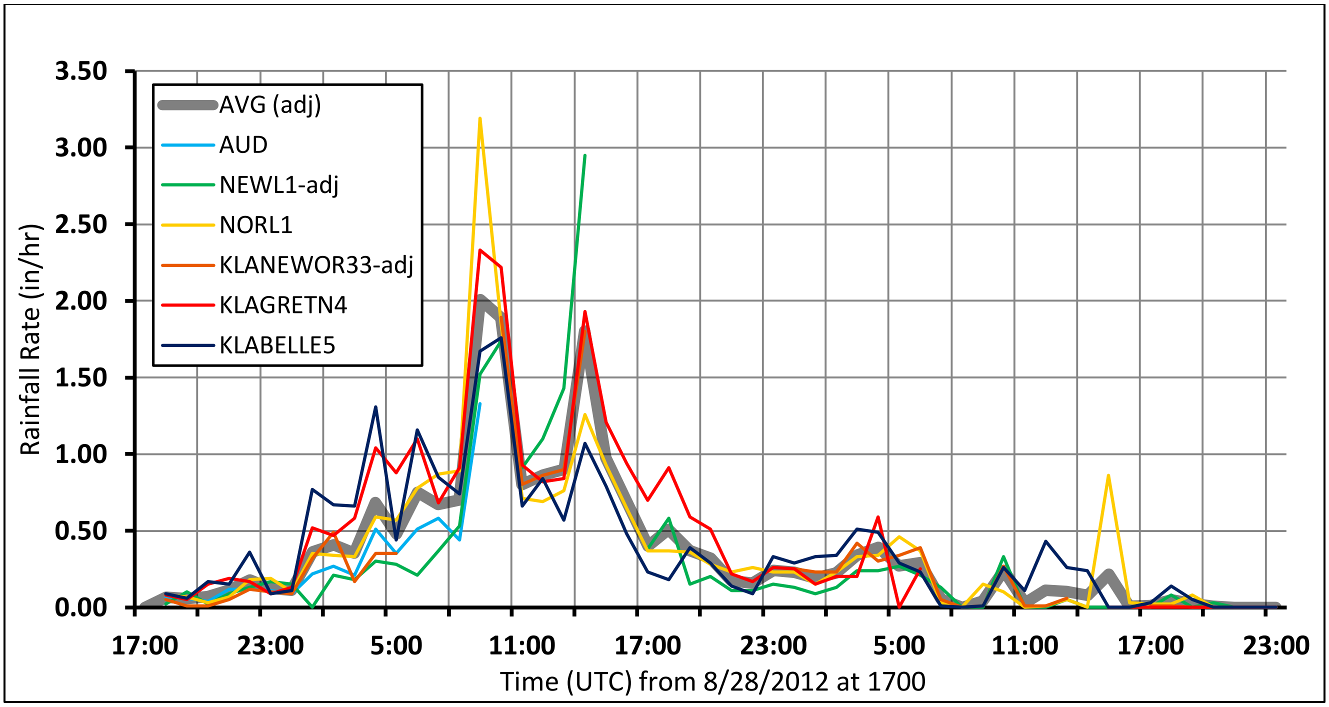


Figure 12. Hourly rainfall rates for official and private gauging stations in the band of extreme rainfall near the Mississippi River. Additional quality control steps were applied to the data since Lincoln et al. (2013) to improve accuracy (see discussion).

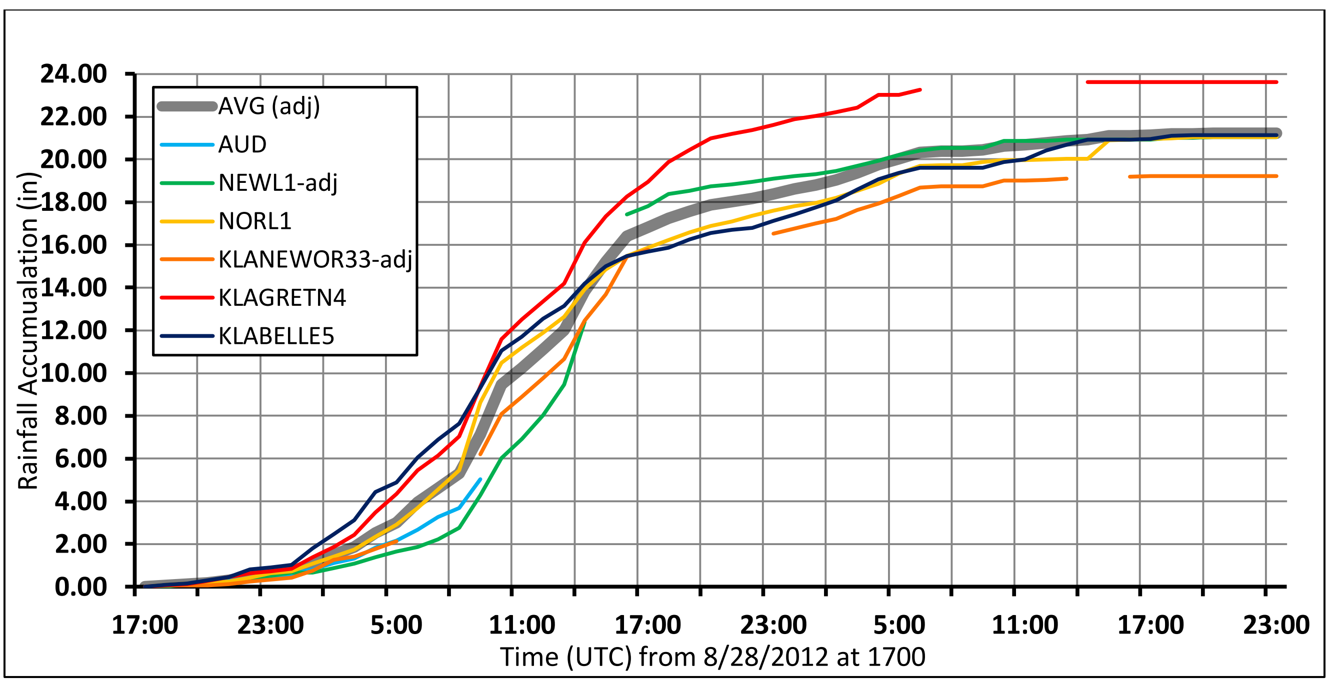


Figure 13. Running rainfall accumulation for the official and private gauging stations in the band of extreme rainfall near the Mississippi River. Additional quality control steps were applied to the data since Lincoln et al. (2013) to improve accuracy (see discussion).

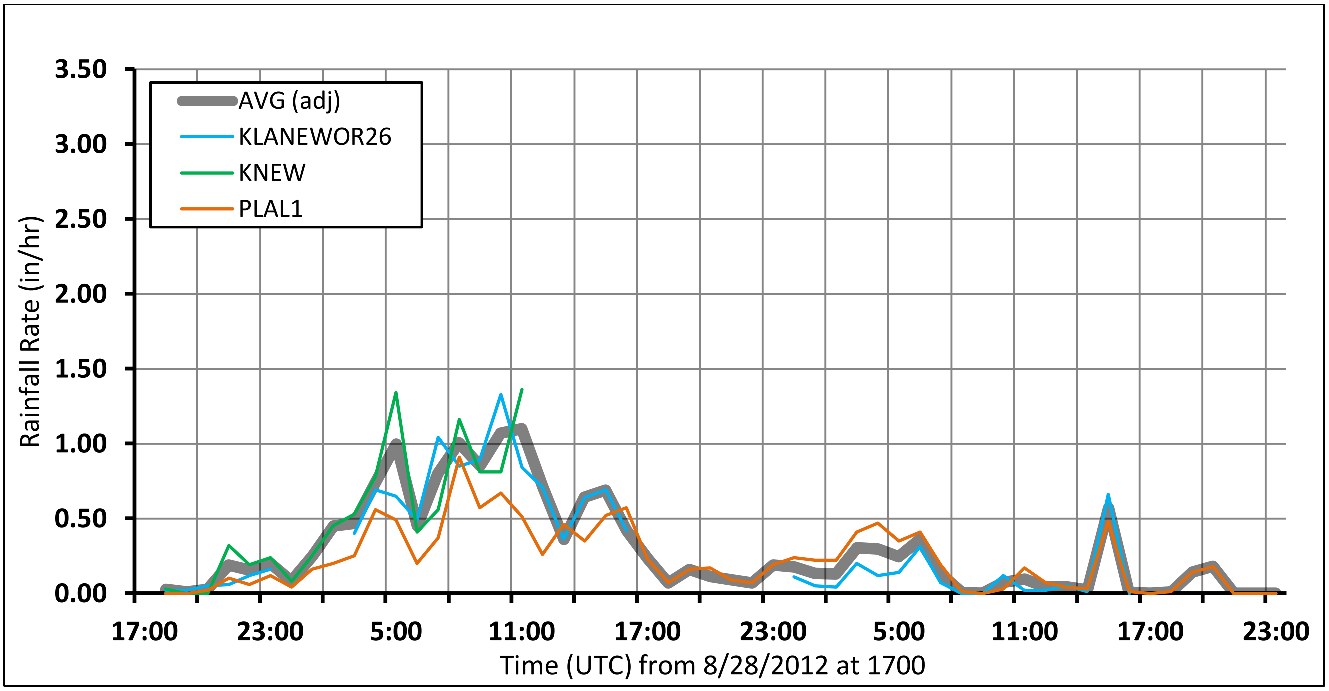


Figure 14. Hourly rainfall rates for the official and private gauging stations near Lake Pontchartrain, just north of the band of extreme rainfall. Additional quality control steps were applied to the data since Lincoln et al. (2013) to improve accuracy (see discussion).

The best-estimate rainfall analysis map was compared to published precipitation frequency estimates in NOAA Atlas 14 (National Weather Service, 2013) to determine the annual probability of this event occurring in a given year. Rainfall across most of the New Orleans metropolitan area over the three day period from August 28th to August 30th was determined to be a 10% annual chance event or greater (greater value is less rare). The heavy swath of rainfall close to the Mississippi River, however, was considerably more uncommon with some areas exceeding the 1% annual chance event (Figure 15); for the purposes of our analysis, we consider rainfall amounts exceeding the 1% annual chance event to be "extreme." As with the rainfall data itself, the annual exceedance exhibited a very sharp gradient. Over shorter durations, rainfall was less extreme (Figure 16), with a running six hour accumulation barely exceeding the 1% annual chance event in the heaviest swath.

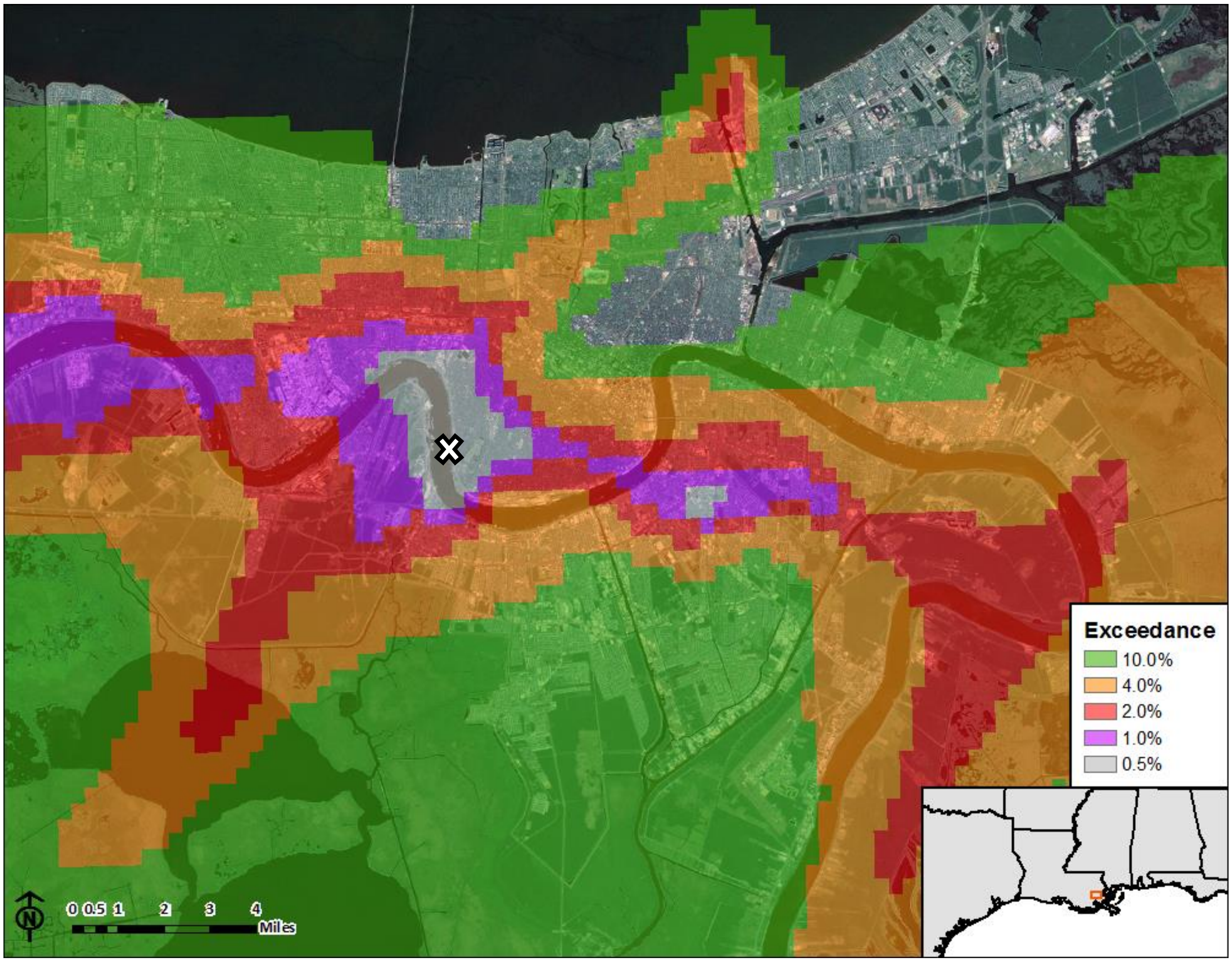


Figure 15. Estimated precipitation exceedance for the best-estimate rainfall analysis map (Figure 10) assuming a storm duration of three days. Exceedance values are the estimated chance of a given rainfall amount occurring in a given year. Extreme rainfall amounts (defined by exceedance of 1% annual chance event) occurred in an isolated swath near the Mississippi River. Most portions of the New Orleans metropolitan area experienced less extreme rainfall totals. The rainfall gauge NORL1 (marked above) is detailed further in Figure 16.

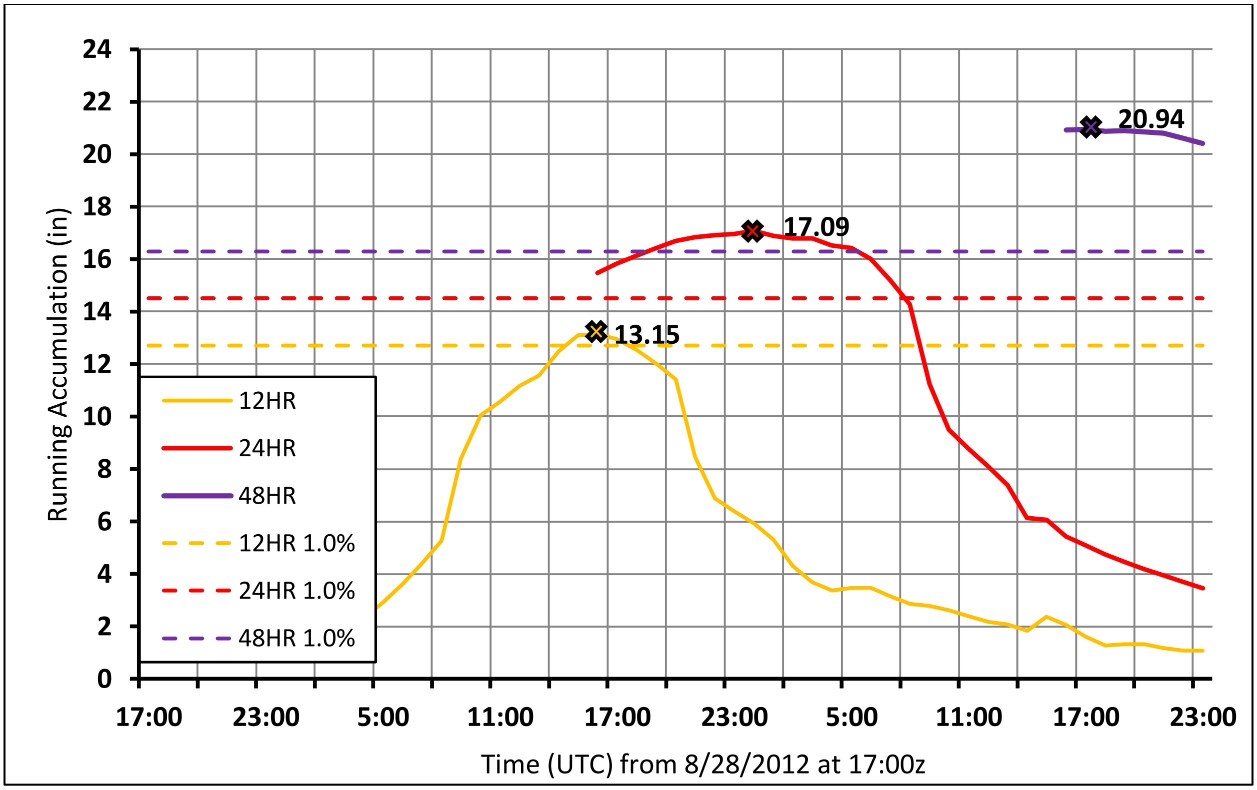


Figure 16. Running accumulations for the rainfall gauge NORL1 compared to published precipitation frequency values. Rainfall amounts become increasingly extreme with longer durations, suggesting that the storm duration, as opposed to the rainfall intensities, was the dominant factor in producing the swath of heavy rainfall.

2e. Modeling runoff volumes from observed rainfall

We determined that to reconcile rainfall estimates with pumping estimates we needed to create a model to estimate canopy interception, surface abstraction, and infiltration. We chose the freely available Hydrologic Engineer Center (HEC) Hydrologic Modeling System (HMS) developed by the US Army Corps of Engineers to perform this task. The HEC-HMS is not a single model, but a suite of multiple models for multiple steps in the process of producing an outflow hydrograph from provided rainfall data. HEC-HMS has been widely used for event-based modeling and event design storm studies. According to hydrologic theory, we assume that the volume of water pumped out of the city is equal to the average runoff, which can be described by the equation:

$$P_{excess} = R - A_{canopy} - A_{surface} - I \quad (1)$$

where P_{excess} is the excess precipitation, or runoff, A_{canopy} is the canopy interception, $A_{surface}$ is the surface abstraction, and I is the infiltration. P_{excess} is estimated from pumping records and R is estimated from rain gauge observations and remotely-sensed radar data, discussed more in Lincoln et al. (2013).

We broke the New Orleans Main polder into various subbasins, each defined by a pumping station. The subsurface flow in the storm drainage system is complicated, and in different events water can flow in different directions toward different canals/pumping stations for pumping out of the city. Even with that caveat, modeling multiple basins has the benefit of better-discriminated rainfall variability and land cover characteristics. We made an attempt to delineate local contributing areas for each pumping station based upon: 1) high resolution elevation data, 2) delineations published in documents from the Gutter to Gulf Initiative (www.guttertogulf.com), and 3) the layout of of the storm drainage network provided by the Sewer System Evaluation and Rehabilitation Program (SSERP) website of SWBNO (http://gosserp.com/).

The resulting HEC-HMS model contains eight (8) subbasins ranging in size from 2.5 to 8.2 mi^2 (Figure 17). Although the pump stations that remove water from the interior drainage network do not pump water into the same canal, we created an artificial confluence downstream of these locations such that we could easily compare modeled volume to observed volume. The model was set to run on a 15-min timestep but we chose to use hourly rainfall data due to the quality-controlled rainfall data available at that interval. Numerous variables were required for the individual modeling methods (US Army Corps of Engineers Hydrologic Engineering Center, 2005). Parameters for abstractions (storages of rainfall that must be satisfied before any rainfall interacts with the soil surface) and soil properties needed to be estimated or derived from available datasets. Soil parameters for the central U.S. were previously derived from SSURGO soil survey data in previous collaboration with the National Severe Storms Laboratory (NSSL; Ami Arthur, NSSL, 2012) and were readily available to use in the infiltration method of the model. Abstractions such as canopy interception and surface abstraction, however, are harder to estimate and can vary widely depending type of tree, building, or soil roughness that is blocking the water. In large events, abstractions are very small relative to the total rainfall, which greatly mitigates uncertainty.

Canopy interception was modeled with the “Simple Canopy” method, which requires one value representing the subbasin-averaged amount of rainfall that must be retained before rainfall continues to the soil surface. Surface abstraction was modeled with the “Simple Surface” method, which requires one value representing the subbasin-averaged amount of rainfall that must be retained, after falling through the canopy, before rainfall continues to the soil surface. Infiltration was modeled with the Green and Ampt method, a physically-based model of infiltration simplified from the Hortons equation. The Green and Ampt method requires the initial soil moisture, the wetting front suction head (the tension force between the water and the soil), and the saturated hydraulic conductivity (the rate of infiltration once soil is saturated). The parameters used in the model are shown in Table 1.

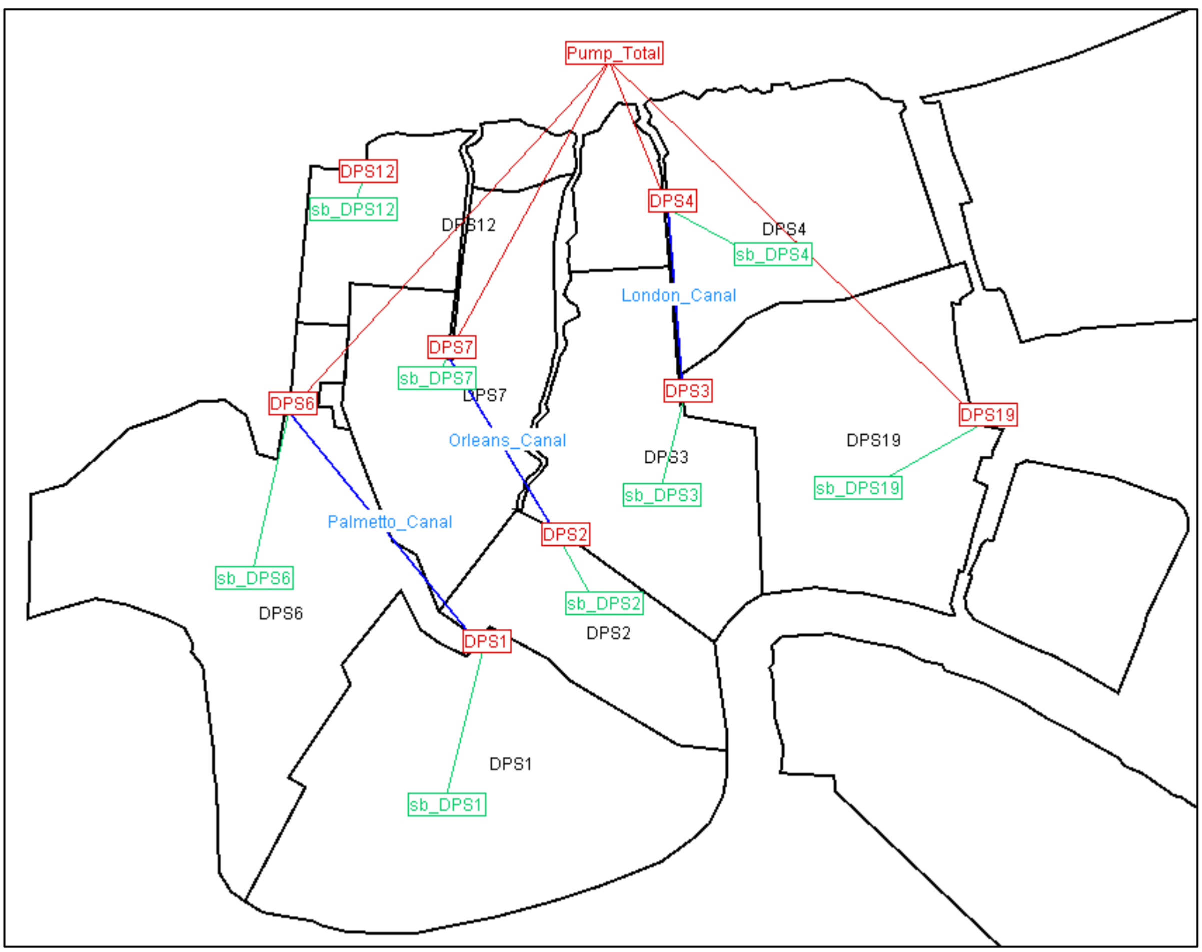


Figure 17. Schematic of the HEC-HMS model developed for the New Orleans storm drainage network.

Table 1. Parameters used in the HEC-HMS model developed for the New Orleans storm drainage network. Although included in the model, modeled flow from pumping station 12 was ignored in the analysis because pumping records were not available.

Subbasin	Area (mi^2)	Canopy Interception (in)	Surface Abstraction (in)	Sat. Hydraulic Cond. (in/hr)	Wetting Front Suction Head (in)	Impervious (%)
1	8.17	0.10	0.20	0.0573	10.6	56.8%
2	2.67	0.10	0.20	0.0005	12.9	79.3%
3	4.62	0.10	0.20	0.0010	10.2	54.4%
4	5.85	0.30	0.20	0.0006	11.5	39.2%
6	8.22	0.20	0.20	0.0767	13.9	48.7%
7	4.81	0.20	0.20	0.0009	11.7	41.1%
12	2.50	0.30	0.20	0.0005	12.9	36.3%
19	5.92	0.10	0.20	0.0013	11.8	57.5%

Subbasin-average rainfall required by the HEC-HMS model was created from both individual gauge averages and from the best-estimate rainfall analysis. To account for temporal variability in the rainfall, hourly rates for gauges within the band of extreme rainfall along the Mississippi River were averaged to create a “River” rainfall timeseries and hourly rates for gauges near Lake Pontchartrain were averaged to create the “Lake” rainfall timeseries (Figure 18). The individual stations used to create these rainfall timeseries are shown by Figure 12 and Figure 14. Model subbasins near Lake Pontchartrain used the “Lake” timeseries and subbasins near the Mississippi River used the “River” timeseries. The rainfall values in both timeseries were weighted to match the subbasin average of the event total produced from the best-estimate storm total rainfall analysis (Table 2).

Table 2. Storm total rainfall for each model subbasin derived from the best-estimate storm total rainfall analysis.

Subbasin	Average Rainfall (in)
1	16.97
2	11.29
3	10.42
4	12.02
6	17.35
7	12.28
12	9.11
19	9.50

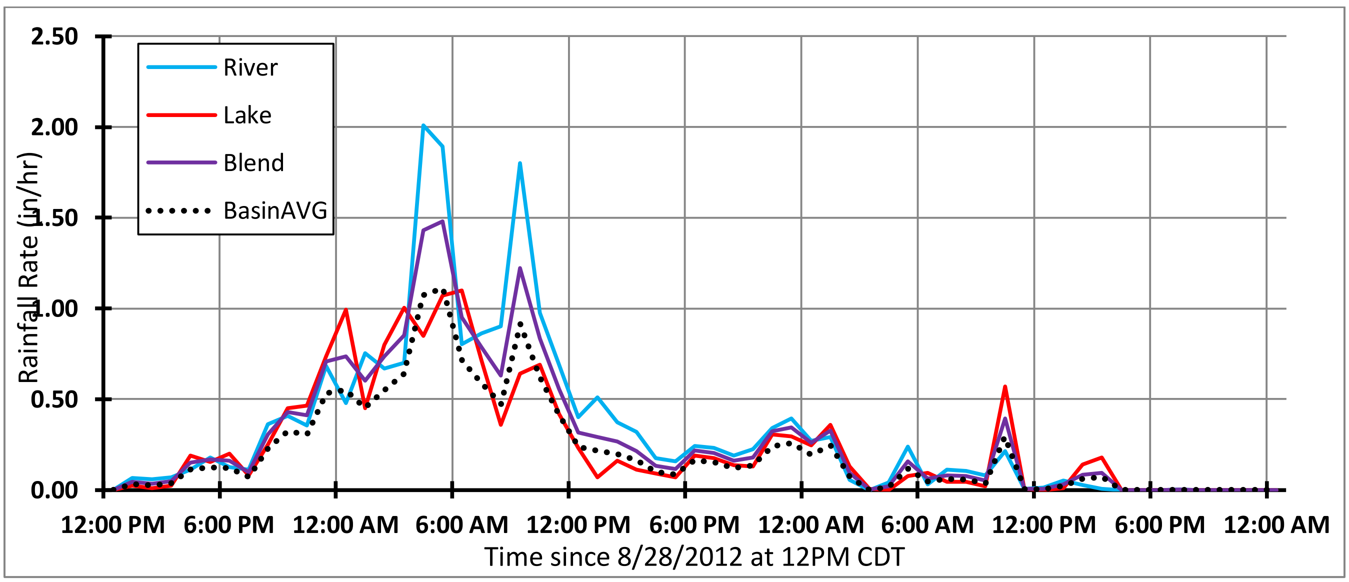


Figure 18. Rainfall timeseries data used to drive the HEC-HMS model. The character of the rainfall differed between areas near Lake Pontchartrain and areas near the Mississippi River. The individual hourly ordinates were weighted for each subbasin of the Main polder depending upon the subbasin-averaged value from the best-estimate storm total rainfall analysis (Figure 10 and Table 2). Hourly rainfall averaged across the entire Main polder (and weighted to match the best-estimate storm total) is displayed as “BasinAVG.”

3. Results and Discussion

3a. Pumping records

The rate of water pumped from each pump servicing the Main polder of New Orleans was calculated from pump curves, and then summarized by pumping station. Pumping rates are illustrated by Figure 19. As mentioned in *2c. Mitigating sources of uncertainty in pumping records*, some water pumped prior to the onset of rainfall should be excluded because it was likely due to prior rainfall; this data is not excluded from the figure. It was also necessary to account for ongoing pumping at the end of the period of record, as previously discussed. The EUD of water pumped from the Main polder of New Orleans during Hurricane Isaac was estimated to be 12.13 inches and 11.94 inches, before and after these adjustments were applied to the data, respectively. The 11.94 inch value should be approximately the same as the runoff from the storm after canopy interception, surface abstractions, and infiltration are subtracted from rainfall.

As a by-product of the pumping record analysis, we also calculated hypothetical maximum pumping rates for the New Orleans drainage network. Pumps have the greatest capacity when the static head is zero, so this situation was used to estimate the maximum possible pumping rate for the system if all pumps were operating simultaneously. Determining the minimum pumping rate when all pumps are in operation simultaneously is somewhat more complicated because pumping capacities would approach zero as static head increases. We used the maximum static head value presented in the pump curves to calculate the minimum rate. Pumping rates provided by SWBNO, referred to as the “nominal” pumping rates, fell between our calculated minimum and maximum. The estimated minimum, nominal, and maximum pumping rates for the New Orleans drainage network were approximately 12,990 cfs, 19,810 cfs, and 23,410 cfs, respectively. The equivalent uniform rates for the minimum, nominal, and maximum pumping rates were 0.50 inches/hour, 0.76 inches/hour, and 0.90 inches/hour, respectively. Rainfall rates and pumping rates estimated during Hurricane Isaac for the Main polder of New Orleans are illustrated by Figure 20.

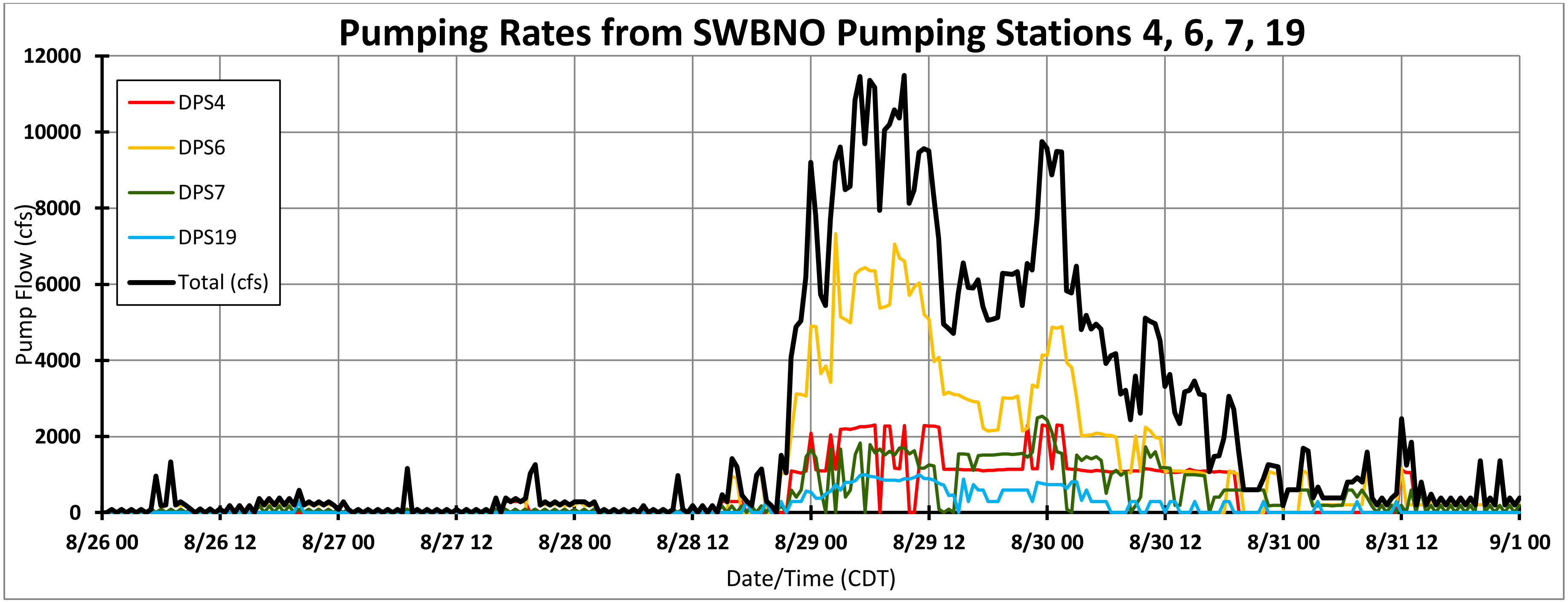


Figure 19. Estimated pumping rates by pumping stations draining the Main polder in New Orleans during Hurricane Isaac.

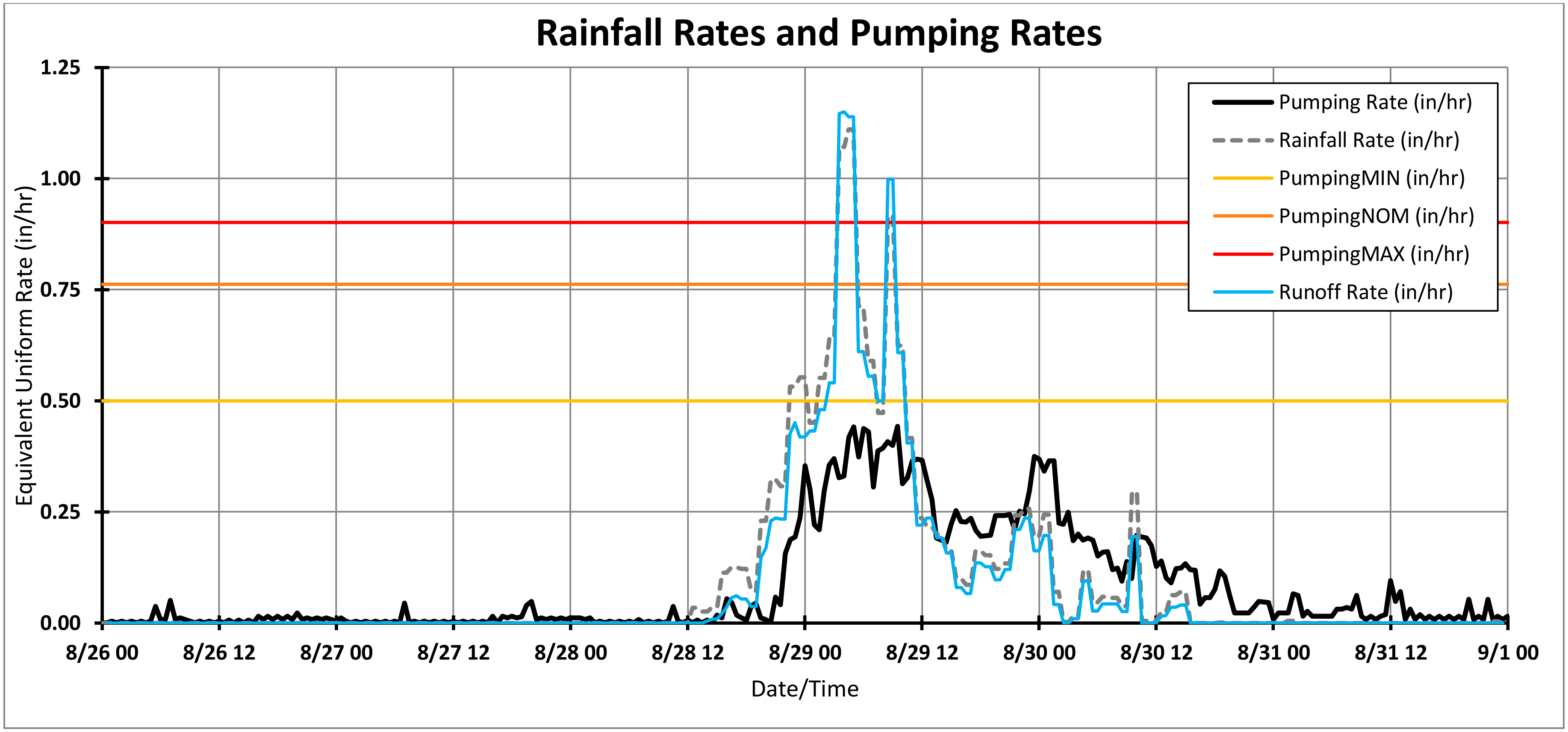


Figure 20. Rainfall and pumping rates for the Main polder of the City of New Orleans during Hurricane Isaac. The hypothetical minimum and maximum pumping rates for the system are specified, as well as the nominal rate provided by SWBNO.

3b. Modeling results

Although we set up the HEC-HMS model with numerous subbasins to better capture rainfall variability, the total modeled runoff from all four exterior pumps (4, 6, 7, and 19) with observed pumping data is assumed to be the best comparison to storm total runoff due to the complexity of the drainage network. To quantify the amount of water lost to canopy interception, surface abstraction, and infiltration (referred to as "loss" in the model), we exported modeled timeseries data from each subbasin, and then computed a weighted average for each timestep to represent the polder-wide value. Modeled rainfall loss ranged from 1.5% (0.17 inches) in the subbasin covering the Central Business District neighborhood to 20.4% (3.54 inches) in the subbasin covering the Uptown neighborhood. Averaged across the entire Main polder, our model indicated 10.2% (1.39 inches) of loss out of 13.54 inches of rainfall, yielding 12.13 inches of runoff. As expected, modeled runoff and estimated pumping for individual subbasins had much more variability than the polder average (Table 3).

For roughly the first half of the rainfall event, runoff rates estimated by the HEC-HMS model exceeded the estimated pumping rates for the Main polder of New Orleans. During times when the runoff rate exceeded the pumping rate, storm water could conceptually be considered "in storage." The rate of storage accumulation was fastest between roughly 2:00AM and 9:00AM CDT on August 29th, reaching about 4.0 inches of equivalent uniform depth before pumping rates began exceeding runoff rates and storage started to fall. To determine how much of this "stored" runoff could have been moving through the drainage network, we attempted to estimate the capacity of the network using GIS methods. We digitized the main canals and box culverts of the system as defined by the SSERP website of SWBNO, using specified widths and heights when available and estimating when unavailable. We estimated that the maximum potential storage of the storm drainage system is approximately 1.3 inches, however the effective storage is likely considerably lower and would be very difficult to quantify. This suggests that over a 36-42 hour period (1:00AM CDT August 29th through 3:00PM CDT August 30th) more water was likely stored, or moving through, the drainage system than could hypothetically be stored by it (Figure 21). We hypothesize that this value is not a discrepancy, but instead is an approximation of the average depth of overland flow in yards and streets during the height of the storm.

Table 3. Summary of results from the HEC-HMS model of New Orleans for Hurricane Isaac.

Subbasin	Rainfall (in)	Loss (%)	Loss (in)	Modeled Runoff (in)
1	16.97	13.5%	2.29	14.77
2	11.29	1.5%	0.17	11.02
3	10.42	2.2%	0.22	10.11
4	12.02	4.3%	0.51	11.43
6	17.35	20.4%	3.54	13.88
7	12.28	3.3%	0.40	11.76
19	9.11	2.7%	0.24	8.77
PolderAVG	13.54	10.2%	1.39	12.13

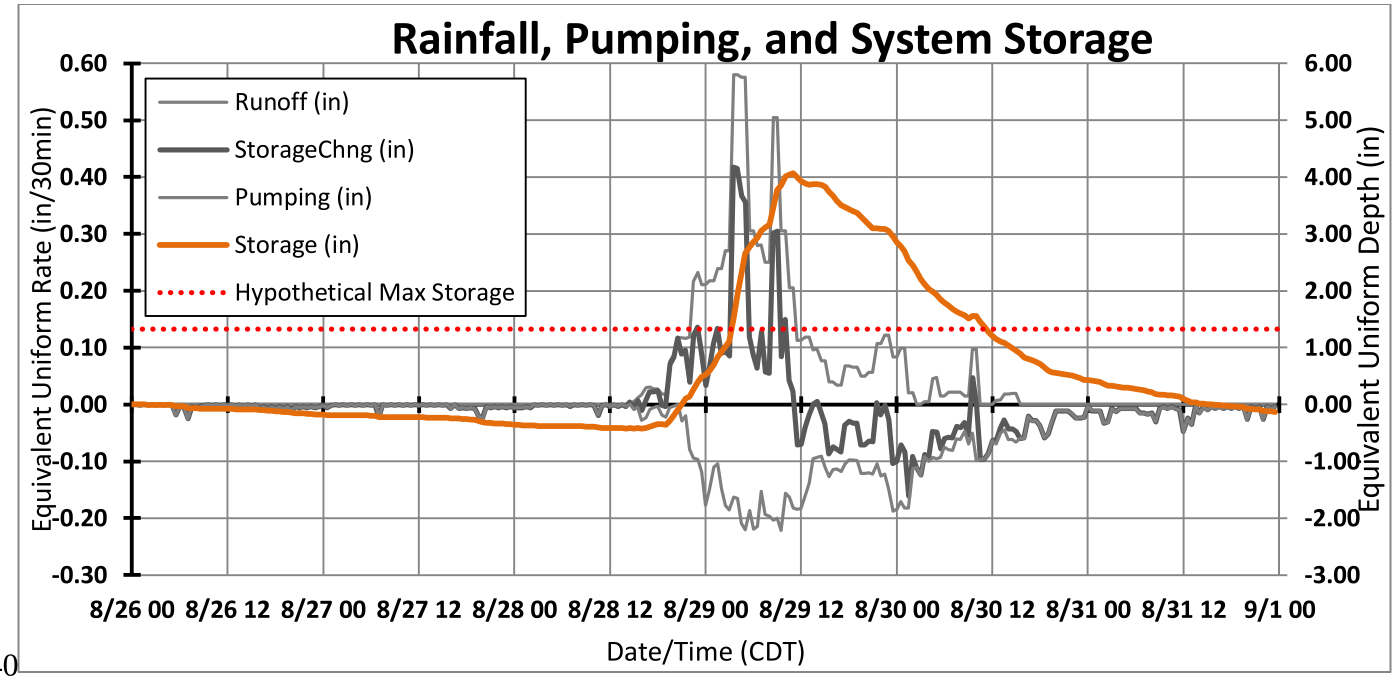


Figure 21. Runoff, pumping, and net change in system storage at each 30 minute timestep. The running accumulation of system storage (relative to August 26th at 12:00 AM) is also plotted to show times that SWBNO pumps are "ahead" or "behind" the accumulated runoff. Hypothetical system storage represents the maximum possible volume of water that could be held by the drainage network

3c. Discussion

There are several sources of uncertainty in our analysis that must be recognized before our results can be discussed. Sources of uncertainty include the digitizing of pumping records, the estimation of pump curves, analysis of rainfall, and estimation of parameters for the modeling of runoff. When possible, we attempted to quantify the potential error from incorrect input data to our analysis, expressed as an equivalent uniform depth, or runoff, across the Main polder.

Because pumping records from SWBNO are done by hand on paper log sheets, digitizing the information required reading different handwriting styles. We also found that there was not a uniform method for logging the tailwater and headwater elevations that would actually be relevant to the operation of the pumps at each pumping station; some stations also logged the water elevation recorded at the debris screens which did not always match elevations closer to the pumps, but the same log sheet column was not always used to specify which measurement was from which location. During some periods, pumping records were taken every hour, even when pumps were in operation, leading to some confusion on whether the pumps were continuously operating or were running for only brief, intermittent periods. To mitigate these concerns with digitizing the pump records, deductive reasoning was used, as well as consensus opinion of several individuals. Entering incorrect information for headwater and tailwater elevations for a single pumping station during periods of highest pumping usage could potentially change the polder-averaged runoff value by 0.01-0.02 inches for each 30 minute timestep that is in significant error. Erroneously indicating one of the largest pumps (1000 cfs capacity or greater) as in operation could potentially change the polder-averaged runoff value by 0.01-0.02 inches for each 30 minute timestep in error.

As discussed earlier, some assumptions and corrections were necessary to use the pumping data from SWBNO. Although we expect that the adjustments improved the data analysis, some non-trivial uncertainty may have been introduced that is difficult to quantify. The greatest uncertainty was likely introduced from the lack of pumping data after 12:00AM CDT on Sept 1st. Pumping, average roughly 250 cfs at the end of the record, continued for an unknown amount of time. We roughly approximate that for each 30 minute timestep, a 1000 cfs error would correleate to roughly 0.01-0.02 inches of polder-averaged runoff, based upon uncertainties described previously.

Pump curves for the SWBNO drainage network were digitized from the IPET report (2006). Some of these pump curves were created from engineering specifications available from the pump manufacturers. Some pump curves were estimated from hydraulic modeling software. When little information was available on a particular pump, the IPET report did not create a pump curve. When no pump curves were available from the report but the digitized pumping records necessitate a pump curve to estimate runoff, we used the nominal value reported by SWBNO and applied that flow to the entire range of static head values. It would be very difficult to quantify the error in polder-averaged runoff due to an incorrect pump curve because of widely-varying pump capacities. We roughly approximate that for each 30 minute timestep, a 1000 cfs error would correlate to roughly 0.01-0.02 inches of polder-averaged runoff, based upon uncertainties described previously. Because we were not involved in the creation of these relationships, however, it is hard to fully quantify potential uncertainty.

Due to the subjective nature of contour analysis, there will be some hard-to-quantify uncertainty introduced from the rainfall estimates. We believe that rainfall estimates were improved since Lincoln et al. (2013) after additional gauges were corrected. The volume of rainfall was higher than the volume of water pumped out of the Main polder of New Orleans, as expected. The volume of rainfall also closely matched results of modeling analysis which we used to estimate losses from abstractions and infiltration. Similar values reported by nearby gauges for hourly rainfall rates and total rainfall accumulations also increases our confidence in our analysis.

The use of a hydrologic model was necessary to estimate losses from abstractions and infiltration and thus calculate runoff from rainfall. This hydrologic model may also have introduced some uncertainty to our analysis. The parameters for the infiltration portion of the model (Green & Ampt equation) were derived from high resolution soil surveys and published values for soil properties, but were not calibrated. The most-sensitive parameter to the Green & Ampt equation is saturated hydraulic conductivity, which approximates the rate of infiltration after the onset of rainfall when the soil surface is saturated. For the city of New Orleans, saturated hydraulic conductivity values were very low due to high clay content and soil compaction through urbanization. In some sections of the city, the values were at the low end of the range allowed by HEC-HMS (just above zero); as such, uncertainty due to the model would mostly be estimated by increasing hydraulic conductivity values. We first set hydraulic conductivity to the lowest allowable value for each subbasin of the polder, which yielded a change in modeled runoff of +1.05in, or +8.8%. Next we changed the hydraulic conductivity for each subbasin by -10%, +10%, +50%, and +100%, which yielded a change in modeled runoff of +0.07in (+0.6%), -0.06in (-0.5%), -0.30in (-2.5%), and -0.56in (-4.7%), respectively. Very large errors in the estimated model parameters are necessary to cause even modest errors in the modeled runoff.

After relevant adjustments were applied to rain gauges, storm total rainfall amounts from Hurricane Isaac were very consistent both spatially and temporally in a narrow swath along the Mississippi River that was once considered questionable. Modeled runoff volumes from the HEC-HMS model for the entire Main polder (12.06 inches) were very close to calculated runoff volumes as estimated via pumping records from SWBNO (11.94 inches); the HEC-HMS model over-estimated the runoff by only 1% when compared to the pumping-derived runoff. These results give us high confidence that the isolated rainfall maximum of greater than 20 inches did, in fact, occur across portions of New Orleans near the Mississippi River during Hurricane Isaac. Analysis of sources of uncertainty suggest that very frequent and/or large errors in input data would be required to yield substantial error in our analysis results.

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5. Conclusions

We continued efforts started in Lincoln et al. (2013) to verify an isolated band of extreme rainfall over portions of New Orleans during Hurricane Isaac. First we summarized New Orleans hydrology and described the impact of Isaac on the city. Then we presented a methodology for estimating the EUD (runoff) from SWBNO pumping records. We also described efforts to further improve our estimates of rainfall to compare to pumping. Next we presented a HEC-HMS model that was used to estimate runoff and losses from the rainfall. We found that the modeled runoff (12.13 inches) very closely matched the runoff estimated from the pumping records (11.94 inches). From this we conclude that there is strong evidence that the isolated, extreme rainfall maximum did occur in sections of New Orleans near the Mississippi River, and despite several inches of runoff going into storage somewhere in the drainage network or on the land surface, no significant flooding was reported.

As noted several times through our studies of rainfall of Hurricane Isaac, gauges can be problematic for realtime rainfall applications. Gauges are prone to under-catch during landfall of tropical systems, and in the case of private stations, gauges may also suffer from power and/or data failure. Bands of heavy rainfall like the one analyzed from Isaac are also small enough that they could conceivably pass between gauges, undetected. NEXRAD radar data is presumed to mitigate this concern because it can provide estimates between gauging locations. As noted in Lincoln et al. (2013), however, these radar estimates substantially underestimated rainfall where the extreme rainfall totals occurred, while over-estimating rainfall in most other locations. This finding suggests that future work should entail better discrimination of warm-rain-dominated precipitation bands and consideration of additional radar-rainfall relationships.

6. Acknowledgements

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