



Tropical Storm Harvey Summary Report – No. 1

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Introduction

The devastation caused by Hurricane / Tropical Storm Harvey to Houston lies not in wind damage nor storm surge, but in the record-smashing rainfall that deluged the entire city and Harris and surrounding counties. After making landfall near Corpus Christi, TX, a high-pressure ridge over SW Texas prevented Harvey from moving much farther inland. Having stalled due to this high pressure system, Harvey continued to pick up moisture from the Gulf of Mexico, thereby generating torrential rainfall that pummeled Houston and its surrounding areas for days. Overall, Harris County, TX received approximately 36 inches of rainfall in the 5-day period between August 25 and 29, 2017, with some areas getting as high as 49 inches. These values far surpassed the 100-year rainfall for Houston of 13.2 inches in 24 hours and 14.5 inches in 48 hours (see Table 1).

Harvey Timeline

On August 17th 2017, the National Hurricane Center (NHC) issued an advisory for a low-pressure system off the east coast of the Lesser Antilles that displayed signs of rotation and strong convective forces capable of strengthening to a tropical storm (see Fig. 1). However, by Saturday August 19th the tropical storm began to lose strength and by nightfall on the same day its wind speeds fell below 39 mph. On Wednesday August 23rd, the NHC reported that Harvey had regenerated into a tropical depression off the east coast of the Yucatan Peninsula. Harvey's new track was identified as N/NW toward the Texas coast, and new rainfall and surge advisories were issued for eastern Texas, Louisiana, and the lower Mississippi Valley (Fig. 2). By Thursday Harvey had become a strong tropical storm with a well-defined eye, low central pressure, and was continuing to strengthen rapidly. At this point, many forecasting models from the NHC showed Harvey becoming a major hurricane before reaching the middle Texas coast (Fig. 3). New NHC advisories warned Texas residents of "life-threatening storm surge, rainfall, and wind hazards" (NHC, 2017).

Hurricane Harvey made landfall at 10 PM Friday August 25th on the middle Texas coast near Rockport, TX as a Category 4 hurricane, with sustained wind speeds of over 130 mph. Harvey then stalled over south Texas for the next day before slowly traveling southeast back toward the Gulf of Mexico. During this time, Harvey generated unprecedented rainfall amounts over Houston and other areas of east Texas. By Tuesday August 29th, rainfall averaged over 36 inches and up to 40 inches across the Houston/Harris County region, with isolated areas near 49 inches.

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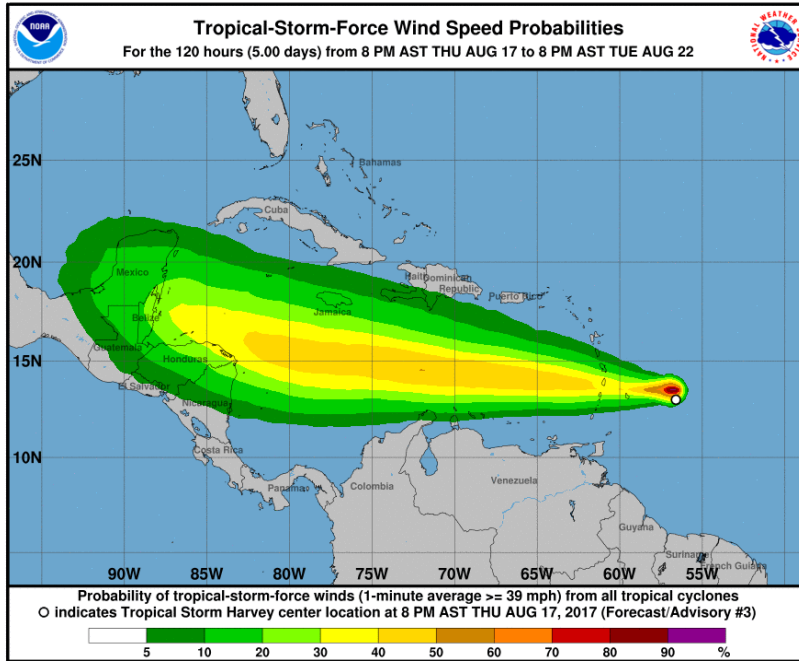


Figure 1: Initial path and wind speeds of Harvey as a tropical storm (Aug. 17th)

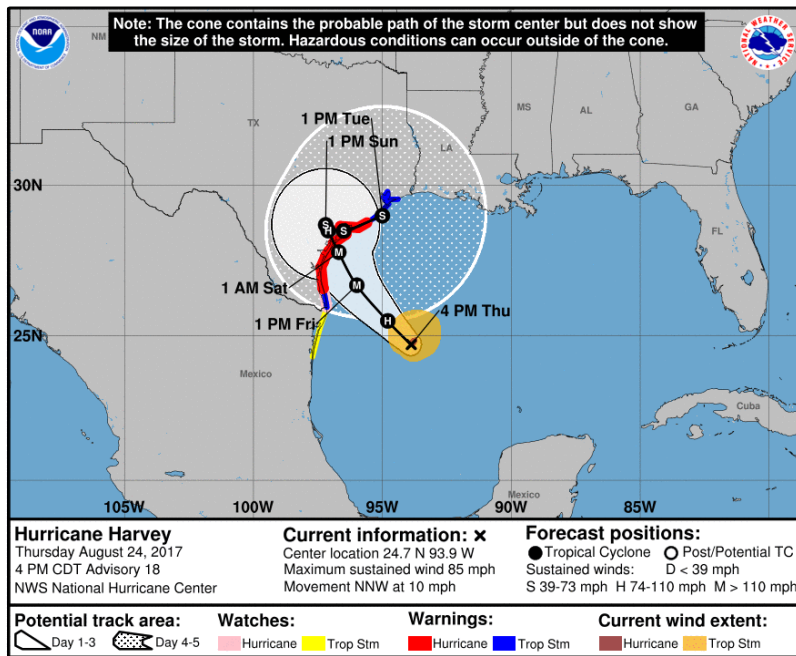


Figure 2: Hurricane Harvey forecasted track and warnings (Aug. 24rd)

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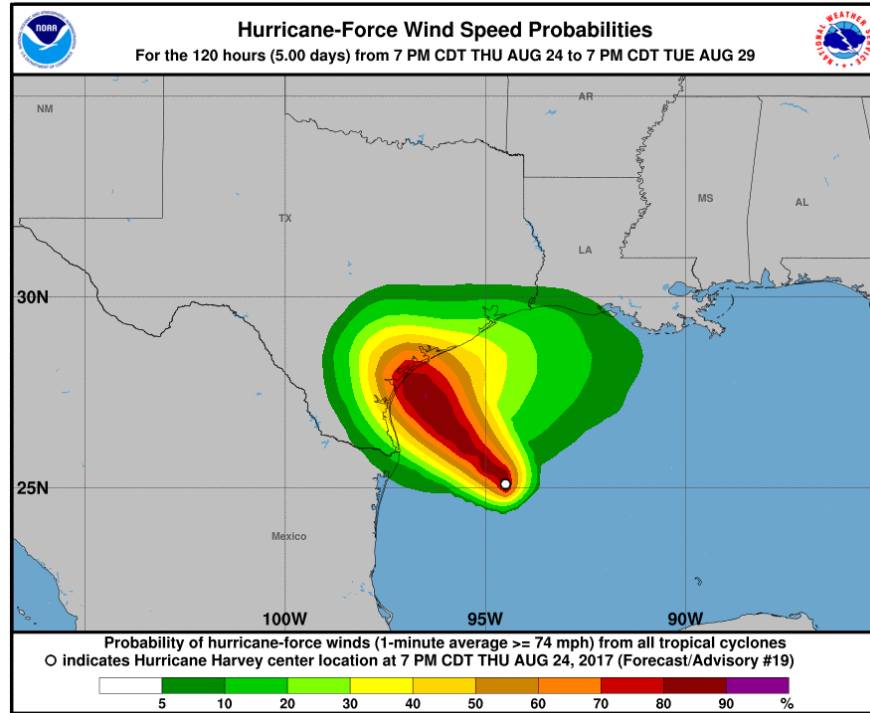


Figure 3: Updated Harvey wind speed probabilities as a major hurricane (Aug. 24th)

Table 1: Rainfall frequency table for Harris County, TX up to 4 day totals (HCFCF 2009)

| Duration | Exceedance Probability (Frequency) | | | | | | | |
|------------|------------------------------------|-----------------|------------------|-----------------|-----------------|------------------|--------------------|--------------------|
| | 50% (2-Year) | 20% (5-Year) | 10% (10-Year) | 4% (25-Year) | 2% (50-Year) | 1% (100-Year) | 0.4% (250-Year) | 0.2% (500-Year) |
| 5 Minutes | 0.7 | 0.8 | 0.9 | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 |
| 15 Minutes | 1.1 | 1.4 | 1.5 | 1.7 | 1.9 | 2.1 | 2.4 | 2.6 |
| 30 Minutes | 1.5 | 1.8 | 2.1 | 2.4 | 2.7 | 3.0 | 3.4 | 3.8 |
| 60 Minutes | 2.0 | 2.5 | 2.9 | 3.4 | 3.8 | 4.3 | 4.9 | 5.5 |
| 2 Hours | 2.3 | 3.1 | 3.6 | 4.3 | 5.0 | 5.7 | 6.7 | 7.6 |
| 3 Hours | 2.6 | 3.5 | 4.1 | 5.0 | 5.8 | 6.7 | 8.0 | 9.2 |
| 6 Hours | 3.1 | 4.3 | 5.1 | 6.4 | 7.6 | 8.9 | 10.9 | 12.8 |
| 12 Hours | 3.7 | 5.1 | 6.2 | 7.8 | 9.2 | 10.8 | 13.3 | 15.5 |
| 24 Hours | 4.4 | 6.2 | 7.6 | 9.6 | 11.3 | 13.2 | 16.2 | 18.9 |
| 2 Days | 5.0 | 7.1 | 8.6 | 10.8 | 12.5 | 14.5 | 17.4 | 20.0 |
| 4 Days | 5.8 | 8.1 | 9.8 | 12.1 | 14.0 | 15.9 | 18.8 | 21.1 |

Tropical Storm Harvey Rainfall

Light rainfall began in Houston on Friday morning (August 25th) and continued on and off until Saturday evening, when heavy rainfall began across the region. Over Saturday night, Harris County received over 10 inches of rainfall in 12 hours, with southeastern parts of the county receiving up to 18 inches. Extremely high rainfall rates were generated across Houston, with up to 6 in/hr in some locations. These rainfall amounts correspond to return periods ranging from a 100-yr event to beyond a 500-yr event (Table 1).

Rain continued to fall across the southeast Texas region from Saturday (August 26th) through Tuesday (August 29th), averaging about 36 inches over most of the area but dumping up to 49 inches in some locations (Fig. 4). The severity and extent of extreme rainfall during Harvey was unprecedented in Houston’s history, and the resulting flooding has been catastrophic for the entire region. Figure 5 shows average 5-day rainfall totals for the watersheds in Harris County, and Table 2 displays the peak rainfall amounts for several heavily populated Harris County watersheds and their corresponding return periods.

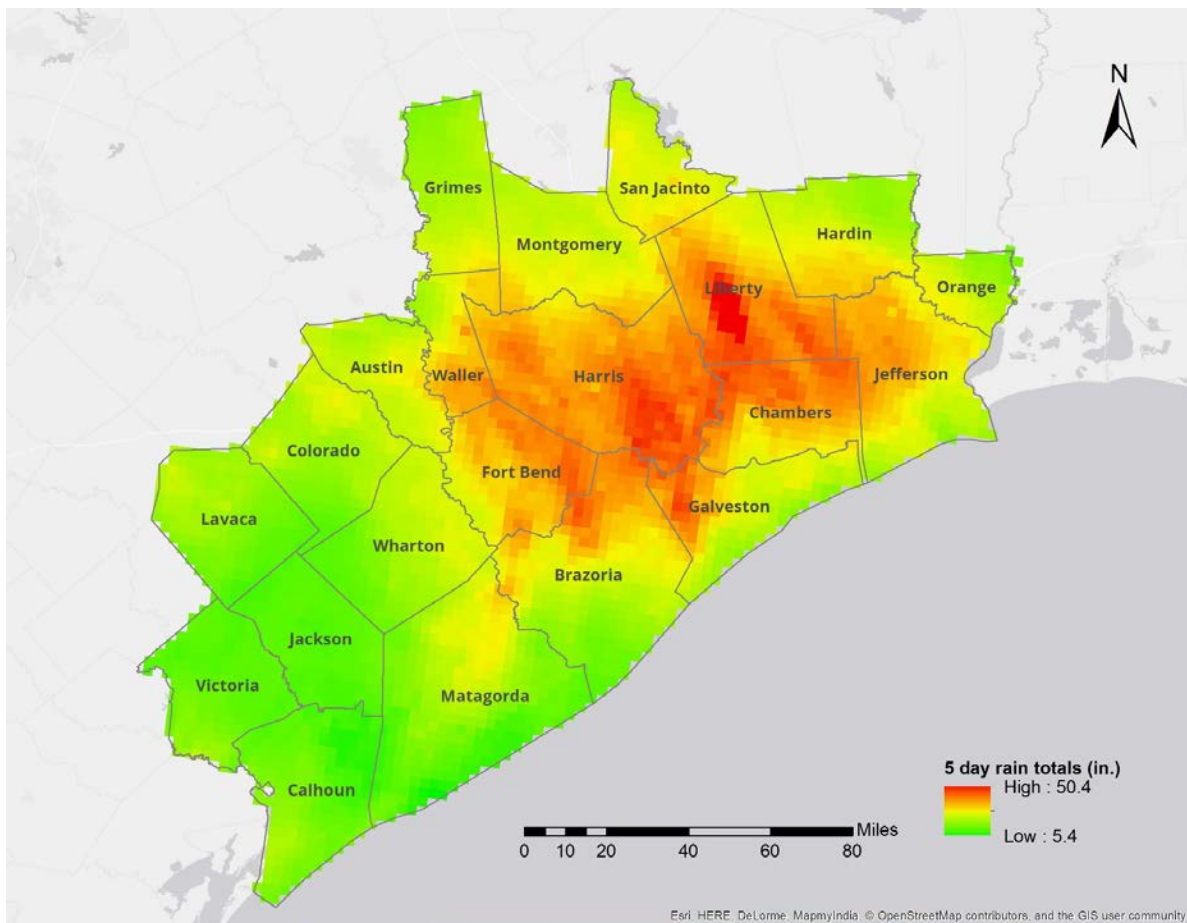


Figure 4: Harvey 5-day rainfall totals for southeast Texas (*Source: NWS AHPS*)

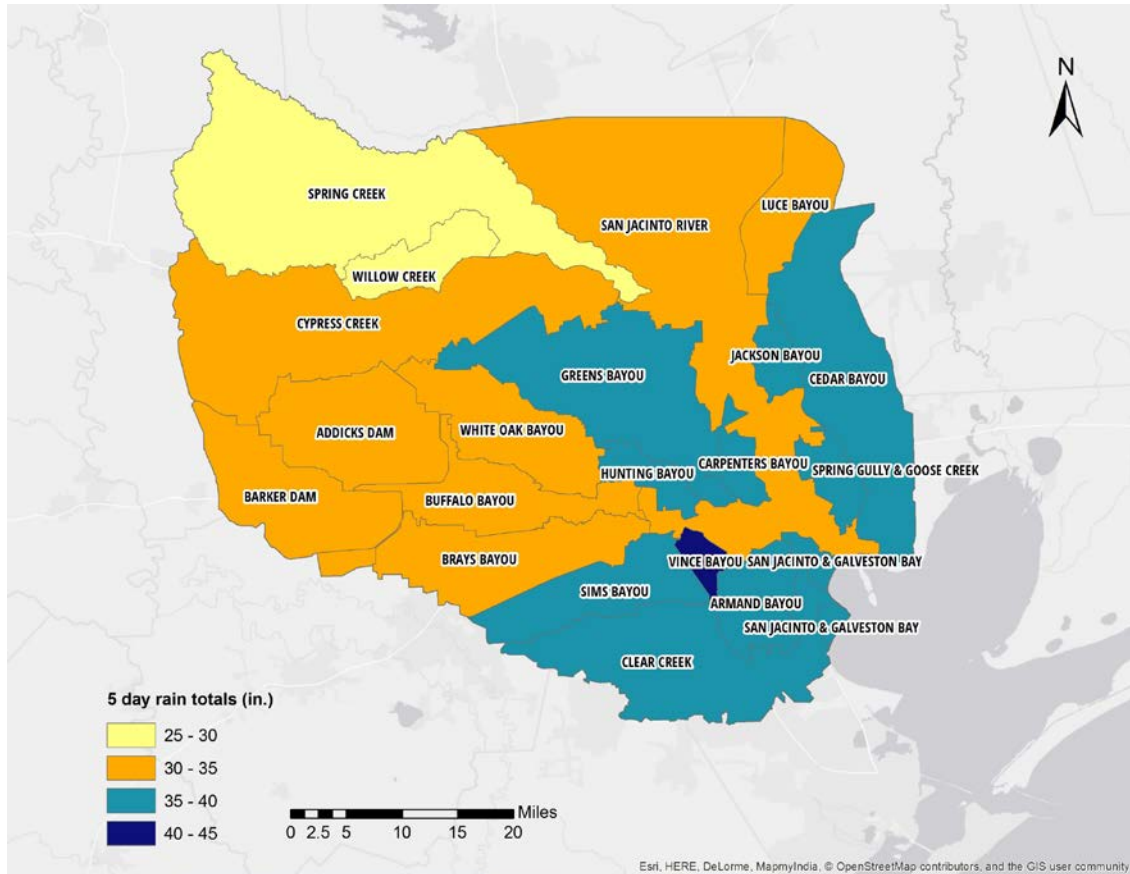


Figure 5: Harvey 5-day rainfall totals for Harris County watersheds

Table 2: Watershed-averaged peak rainfall intensities

| Watershed | 6 hr. Max | 12 hr. Max | 24 hr. Max | Return Period |
|------------------------|------------------|-------------------|-------------------|----------------------|
| Cypress Creek | 6.49 | 10.73 | 16.12 | 250 - 500yr |
| Clear Creek | 12.80 | 15.62 | 19.11 | 500yr |
| White Oak Bayou | 6.84 | 11.65 | 16.62 | 250 - 500yr |
| Brays Bayou | 7.78 | 12.37 | 16.21 | 250yr |

Harvey generated massive amounts of rainfall due to its almost stationary position near the coast. As winds rotated around the eye of the storm they picked up significant moisture over the Gulf waters and released this moisture as high-intensity precipitation over the Houston region. In addition, Harvey’s strength and precipitation potential were greatly helped by the unusually warm waters present in the Gulf of Mexico during the days before landfall. NOAA estimated that sea-surface temperatures near Texas were up to 7.2° F higher than the long-term average, reaching almost 90° F before Harvey made landfall (Meyer, 2017). Climate

scientist Katharine Hayhoe explained that these warm waters provided more energy to the storm, increased air moisture by allowing higher evaporation rates, and consequently resulted in higher precipitation rates inland (Meyer, 2017).

Harvey Flooding Levels

Flooding levels and impacts of Harvey are beyond any previous storm in Houston's history, or for that matter, U.S. history in terms of overall extent. Due to the intensity and sheer volume of rainfall over the region, flooding has been widespread and catastrophic. All 22 of Houston's major bayous spilled over their banks, with some exceeding 10 ft. above the channel banks. Additionally, Houston's two major reservoirs, Addicks and Barker, were quickly inundated by rainfall and their levels reached the top of their emergency spillways. The Brazos River in Fort Bend County, which drains an area larger than 45,000 square miles, quickly entered major flood stage as its water level exceeded the previous record stage by almost 2 ft and flooding along the Brazos River in Ft. Bend County overwhelmed protective levees in some areas. North of the city, the San Jacinto River also flooded.

Bayou Flooding throughout Houston

Riverine flooding depths and extents resulting from Hurricane Harvey will be more severe and widespread than previous severe storms in the Houston area. An initial estimate by FEMA suggests that around 80,000 homes could be flooded in the Houston area for Harvey (FEMA, 2017). To get a preliminary understanding of the scope and magnitude of flooding, Figure 6 depicts the maximum stage levels recorded at each stream gauge in Harris County. Each of the 22 watersheds in Houston experienced riverine flooding from over-topping.

In Cypress Creek watershed, some stage gauges recorded water surface elevations over 10 ft. above the channel banks. The catastrophic flooding levels in Cypress Creek watershed during Hurricane Harvey surpassed levels observed during the Tax Day flood of April 2016. During the previous 2016 storm, almost 1700 homes were flooded in Cypress Creek watershed (HCFCD, 2016). Residential flooding in Cypress Creek from Hurricane Harvey will far surpass the damage observed during the Tax Day storm. Figures 6 and 7 clearly demonstrate the immense flooding that took place all across the Houston area.

In Brays Bayou watershed, substantial flooding occurred in the Meyerland neighborhood, which has been plagued by floods in the past two years. Both the 2016 Tax Day storm and the 2015 Memorial Day storm resulted in residential flooding of approximately 1400 and 1200 homes respectively in Brays Bayou watershed. These damages occurred under rainfall conditions much less severe than TS Harvey. Other major watersheds with a history of recent flood damages include Greens Bayou, White Oak Bayou, and Buffalo Bayou. While water levels in the White Oak Bayou and Brays Bayou watersheds receded relatively quickly (~12hrs), stage hydrographs in Cypress Creek watershed remained elevated above the banks for over 3 days after the occurrence of peak rainfall intensity. (See Fig. 7).

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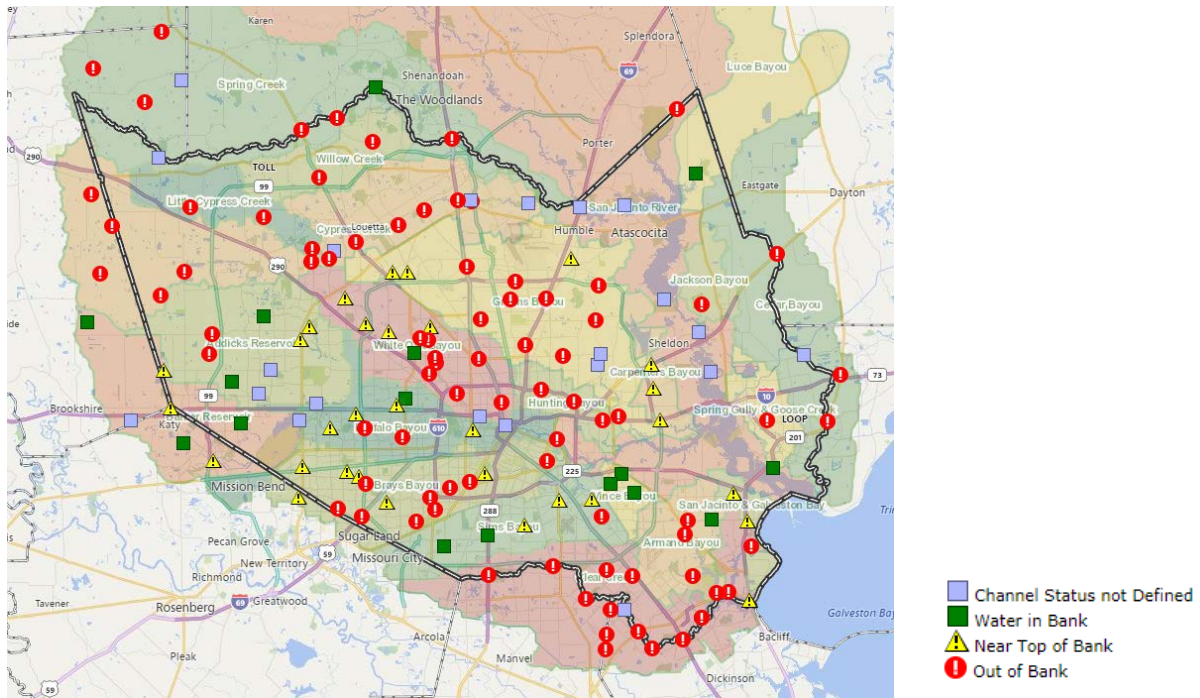


Figure 6: Over-topping of Houston bayous (Harris County FWS 8/27)

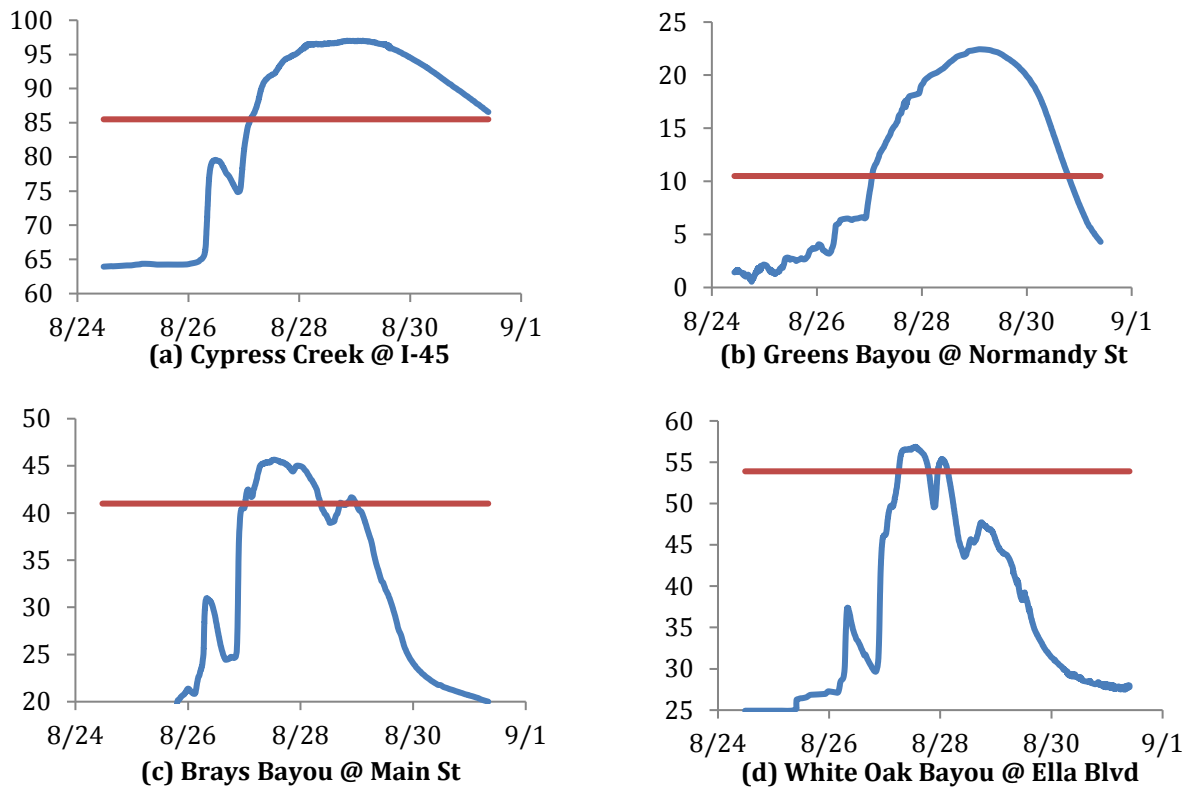


Figure 7: Stage hydrographs (top of bank shown in red) during Harvey for downstream locations in (a) Cypress Creek, (b) Greens Bayou, (c) Brays Bayou, and (d) White Oak Bayou

Addicks Reservoir and Barker Reservoir Flooding

In addition to the extensive riverine flooding along Houston’s bayou system, the city’s two main floodwater storage reservoirs, Addicks and Barker, were also overwhelmed by inflows from upstream tributaries (see Fig. 5 for locations on west side). The portion of Buffalo Bayou above the two reservoirs, which serves as the primary inflow to Barker reservoir, went into flood stage by August 27th evening. In the Addicks watershed four main tributaries flow into Addicks, and these creeks went into flood stage as early as August 26th, and their contributions to Addicks reservoir quickly caused its water surface elevation to enter flood stage as well (Fig. 8). By the morning of August 28th water levels in the reservoirs were spilling into nearby residential subdivisions and Harris County Flood Control District (HCFCD) alerted residents near the Addicks and Barker dams that flooding was imminent. It is worth noting that of the two reservoirs, Addicks generated a much higher stage than Barker and went over the spillway.

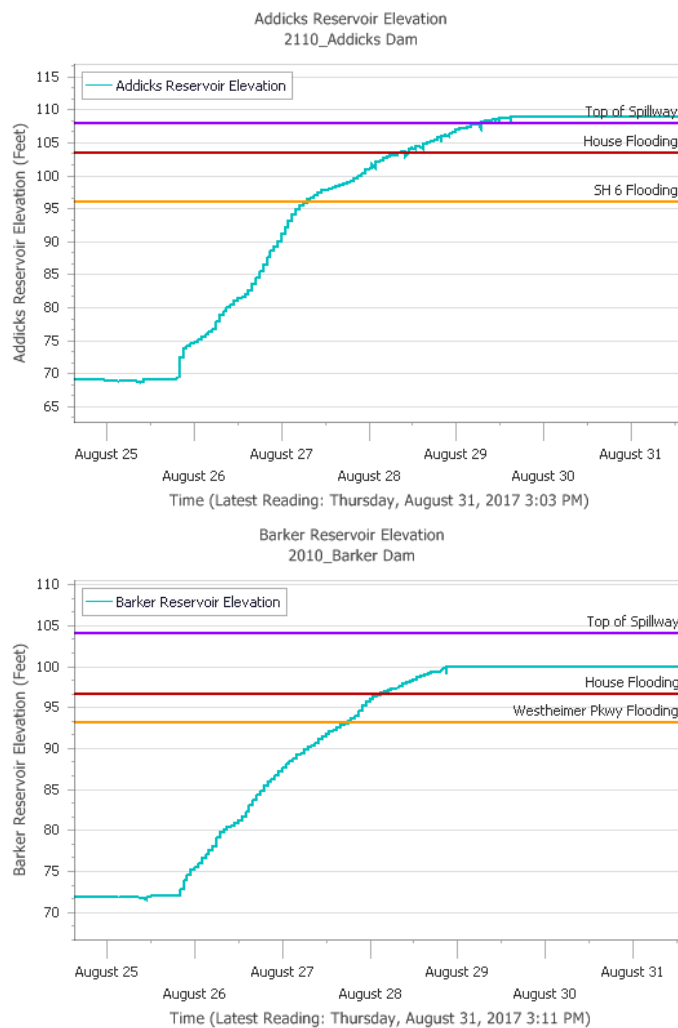


Figure 8: Water levels in Addicks (top) and Barker (bottom) reservoirs

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Given that water levels at both Addicks and Barker had risen at an alarming rate and quickly reaching their full capacities, the U.S. Army Corps of Engineers (USACE) authorized controlled releases from each reservoir into Buffalo Bayou. On August 29th, releases from Addicks and Barker began and were gradually increased to a combined release of about 16,000 cfs into Buffalo Bayou. This action was authorized even though Buffalo Bayou had already spilled over its banks, and the additional inflow would have likely resulted in more flooding in Buffalo Bayou watershed. The USACE believed that a gradual inflow to Buffalo Bayou from the reservoirs would cause less damage than the possibility of either reservoir over-topping their main spillways and inundating downstream areas with no warning. To help residents of the Buffalo Bayou watershed prepare for the gradual flow increases, HCFCFD released a map showing areas of possible inundation (Fig. 9). However, the reservoir impact has created a major issue for residents living in that western part of Houston, with flooding that might last for weeks.

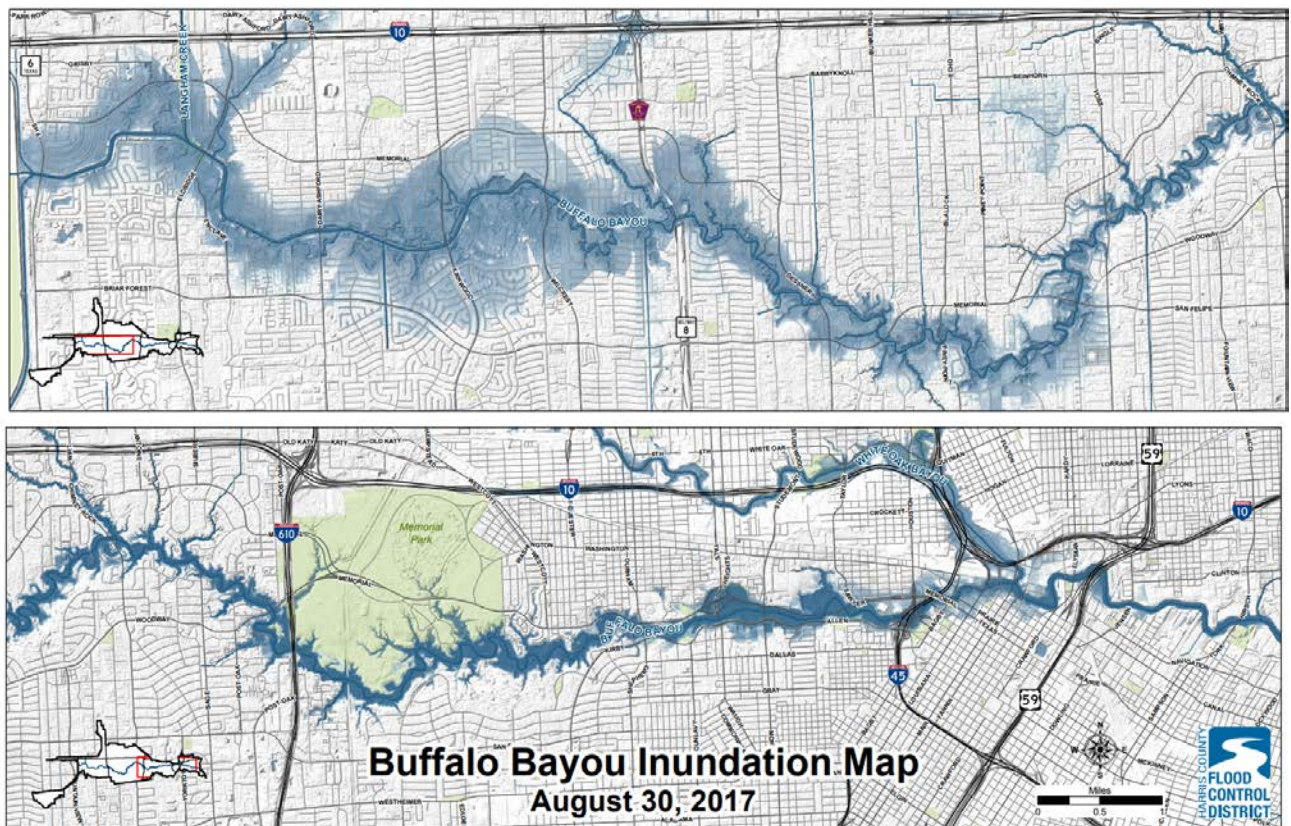


Figure 9: Inundation potential just downstream of Addicks and Barker (top) and near downtown (bottom) due to controlled releases (HCFCFD 2017)

Brazos River Flooding

Along the Brazos River in Fort Bend County stage levels in the river rose to dangerous levels in the wake of Harvey's intense rainfall, prompting evacuation orders to be issued for many

neighborhoods and subdivisions. On August 29th, Fort Bend County hydraulic models forecasted the elevation in the Brazos River at Richmond, TX to reach 59 ft, but in actuality it fortunately only reached just over 55 ft. Although there are flood protection levees along the banks of the Brazos River, these levees only guarantee protection to the 100yr return period. Predictions showed potential inundation areas near Richmond, TX with 56 ft and 58 ft stage in the Brazos River, which are above 100yr levels. Models showed neighborhoods like the massive Sienna Plantation subdivision and Pecan Grove subdivision completely inundated. Consequently, emergency managers in Fort Bend County issued 11 mandatory evacuation orders and 10 voluntary evacuation notices for neighborhoods along the Brazos River. Ultimately, stage peaked in the Brazos River on August 31st night at 55.2 ft. Although this elevation was substantially lower than the initial forecasts, it still broke the previous stage record of 54.7 ft, and resulted in devastating flooding to thousands of county residents.

San Jacinto River Flooding

Along the San Jacinto River, flooding levels were so high that many stream gauges along the river stopped recording or malfunctioned. On the West Fork of the river near Humble, TX water levels were almost 20 ft above channel banks (Fig. 11). At the Lake Houston Dam, unprecedented water levels resulted in reservoir levels overtopping the spillway by almost 10 ft. Further downstream, near the Houston Ship Channel, a stream gauge recorded water levels greater than 6 ft above bank before the gauge stopped recording. Residents of the Humble and Kingwood areas were completely inundated by riverine flooding, with hundreds of rescue requests both through the Houston Police Department (HPD) and through social media.

Human Impact

Harvey has left many Texans stranded and displaced across the region from Corpus Christie to Beaumont. As of Monday, August 28th, Houston officials had responded to over 60,000 distress calls (PBS, 2017). On August 30th the Coast Guard was still receiving 1,000 emergency calls per hour (ABC News, 2017). Approximately 13,000 people have been rescued in the Houston area and 18,000 in Southeast Texas (The Weather Channel, 2017). Currently, the death toll due to Harvey nears 60, but may climb higher as rescues continue with receding water levels (Houston Chronicle, 2017).

An estimated 10,000 evacuees have taken refuge inside the George R. Brown Convention Center (ABC News, 2017), where cots have been set up (Fig. 12). More shelters continue to open every day, including the NRG Stadium, home of the Houston Texans. FEMA administrators have said that they are operating 230 shelters and housing 30,000 in shelters across the state (ABC News, 2017).



Figure 10: Evacuees on the cots at the George R. Brown Convention Center

At the height of the storm, an estimated 300,000 homes were without power across Texas (New York Times, 2017). On August 31st, there were 75,000 power outages in the Houston area and 43% of those outages were inaccessible to crews due to high water (ABC News, 2017). Jeff Lindner, a meteorologist with HCFCD, estimates that 25-30% of Harris County was under water (CBS, 2017).

Conclusions

The devastation wrought by Hurricane/Tropical Storm Harvey in Texas has broken flood records across the state. With rainfall totals averaging 36 inches in 5 days and reaching 49 in., extreme riverine flooding across Houston's bayou system, thousands evacuated citizens as well as thousands of rescues, and damages expected to reach over 100 billion dollars, the recovery effort will take months if not years. This storm must serve as a catalyst for change.

Specifically, by prompting engineers and city planners to re-examine existing flood infrastructure and policy, and by paving the way for the development of long-term solutions that will protect Houston and ensure its resilience in the face of future extreme storms and climate change impacts.

Recommendations

In the paragraphs below, some ideas about where we start and what concepts might be viable are presented. These are not intended to be exhaustive but rather to initiate a conversation about designing Houston for the future.

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1. A clear starting point is to identify the areas that did not flood during TS Harvey. These areas will form the spine of the Houston of tomorrow.
2. There are several areas, mostly deep in the mapped flood plains, where multiple floods have damaged homes multiple times. We need to identify these areas and remove these homes from harm's way, as it is unlikely we can develop strategies to protect them from these severe rainfall events. In order to do this, there will need to be massive buy-out program. A fair but extensive program of home buy-out and removal must be established.
3. Based on the above two steps, three clear zones of strategy will become evident. They should be mapped and separate policies considered for what might be considered the "safe" area, a "transitional" area where only single event flooding has occurred and the "buyout" area which will become a key element of our future green infrastructure that will, along with the "safe" area, provide urban design definition to the Houston of tomorrow.
4. Addicks and Barker Reservoirs are excellent flood control reservoirs which are in major need of repair and redesign. There are several strategies that should be considered here.
 - a. The Corps of Engineers has to fix the deteriorated levee conditions that caused these reservoirs to be classified as two of the six most dangerous flood control dams in the United States. Although some work has been completed, more needs to be done. These two reservoirs have accumulated extensive amounts of silt and sediment over the last sixty+ years of operation. That sediment needs to be removed so that at least two or more feet of capacity can be restored to each of these reservoirs – capacity that was desperately needed during Harvey.
 - b. These two reservoirs, although designed for multiple-day flood events, are not large enough for the rain that fell during Harvey, causing extensive flooding downstream on Buffalo Bayou as well as upstream behind the dams. A new flood control reservoir has been suggested upstream in the Katy Prairie area, and at least partially designed by HCFCD that, if constructed as proposed, would offer significant relief to Addicks Reservoir. This upstream alternative should be pursued immediately.
5. Severe storms are in our future. Whether you say it is climate change or just "weird weather", the fact is that we are looking at larger, more severe storm events than we have previously contemplated. It is hard to grasp how large and how serious these storms can be. Harvey, for now, has defined the edge of severe rainfall events, but we have not seen the worst hurricane surge that is likely to occur at some point in the future. The fact that we have seen a near 100-yr, and two greater than 500-yr events in just three years indicates that something is not correct with the way we predict storms in the Gulf Coast. We have to understand that these storms indeed can and will happen, and Harvey showed us that fact. We must determine more accurate and appropriate

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100-year and 500-year rainfall events for the design, planning and engineering that will occur after Harvey.

6. Native prairies and wetlands still exist in the western and northwestern portions of Harris County. We should establish programs to preserve these areas because they have an amazing natural capacity to infiltrate and store rainwater and runoff and store it either in the soil or behind constructed levees.
7. We need tools to help us live with the floods that we know are in our future. We need the best flood warning and flood information system in the United States, one that matches the extent of our flooding problem which is among the worst in the United States according to pay-outs on flood insurance (and that was before Harvey). With the technology of today, we should be able to obtain up-to-date information about rainfall intensities, bayou conditions and flooded roads and intersections on smart phones. No one should die by driving into a submerged intersection that is known to have problems during rain events.
8. Our pattern of development has been outward from the center of the City up the watersheds of the various bayous and creeks. As such, our new development has dumped increased runoff from development on our older downstream subdivisions and commercial structures. Inadvertently, we have dumped runoff on older neighborhoods while attempting to keep flood control costs lower in the new development, effectively subsidizing new development on the backs of the downstream residents. Fort Bend County has much more stringent drainage regulations than does Harris County and it fared better in the storm than did Harris County. Ft. Bend has had excellent economic growth. We can design better, safer subdivisions and still thrive economically.
9. We need to learn better how to live with floods that impact us, just as the Dutch have experienced. We need to help our citizens learn more about flooding risk, especially new arrivals to Houston, and how floods may impact them. We should have easily available information about flood plains and their accuracy (at least until new ones come out), where the major flooding occurred and where the repetitive flooding has occurred. Those moving into hurricane evacuation zones should be informed of this fact. Well informed buyers make good decisions.

It is a mixture of strategies both structural and non-structural that will lead us to find better ways to live here on the Texas coast.

References

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