# Hurricane Harvey

BILL KAPPEL
DOUG HULTSTRAND

## ABSTRACT

Rainfall reached historic levels over the coastal regions of Texas and Louisiana during the last week of August 2017 due to Hurricane Harvey. Although extreme rainfall from this type of landfalling tropical system is not uncommon in the region, Harvey was unique in that it persisted over the same general location for several days, which resulted in devastating flooding and severe stress to infrastructure in the region.

## INTRODUCTION

Rainfall from Hurricane Harvey resulted in some of the greatest accumulation ever recorded in the United States and was most extreme at large area sizes (greater than 5,000-square miles) and long durations (greater than 24 hours). However, even at smaller area sizes and shorter durations, the storm still produced record-setting rainfall. This was extremely unusual and points to the fact that the storm was truly a Probable Maximum Precipitation (PMP) event.

PMP is "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year" (World Meteorological Organization, 2009). Therefore, PMP represents a theoretical upper limit of the greatest amount of rainfall that can accumulate, and the analysis of Harvey rainfall confirms that it reached that level. However, from a probabilistic perspective, PMP does not have zero probability of occurrence but instead represents a very rare likelihood of occurrence (e.g. $10^{-6}$ or less). Therefore, PMP events can and do occur, as demonstrated by Hurricane Harvey.

At the same time, Applied Weather Associates (AWA) had recently completed a statewide PMP study for Texas, updating the previous PMP values provided in HMR 51. Of course, this meant the timing of the Harvey rainfall was perfect for testing and comparing the newly developed values.

Texas is home to some of the most extreme rainfall events ever observed in the United States, and in some cases the world. Favored locations in the state include the Edwards Platueau and immediate coastal regions from Corpus Christi through Beaumont-Port Arthur and southern Louisiana (Figure 1 and Figure 2). These regions are favored because of topographic interactions with moisture flowing in from the Gulf of Mexico, merging with the terrain along the Balcones Escarpment, along with hurricane landfall interaction with coastal terrain. In addition, along the coastal sections of Texas during hurricane season, atmospheric steering currents are very weak. This often results in slow movement of the landfalling tropical systems in this region, allowing heavy rain to accumulate over the same general region for several days.

Devastating flooding from Harvey was the result of the extreme rainfall, with the hardest hit region extending from the Houston metropolitan region through southwestern Louisiana. Fortunately, no high hazard structures failed during the event.

Within recent history, similar storms have also occurred in this area (e.g. Hearne 1899, Beulah 1967, Alvin 1979, Allison 2001). So, what made Harvey different?

Harvey was unique because it was supplied by near-record levels of moisture from the Gulf of Mexico. During its movement from the Yucatan Peninsula through the Bay of Campeche towards Texas, warm sea surface temperatures provided exceptional amounts of moisture. Further, atmospheric steering currents were very weak, allowing Harvey to remain over the same general area for several days. A final unique aspect was the storm's position once it made landfall. In this case, Harvey was in a position close enough to the coast that allowed extremely moist air to continue to feed into the storm while the storm was able to retain its warm-core tropical characteristics and efficient rainfall production mechanisms.

Several excellent analyses and discussions of the meteorological environment associated with Harvey's formation, track, and

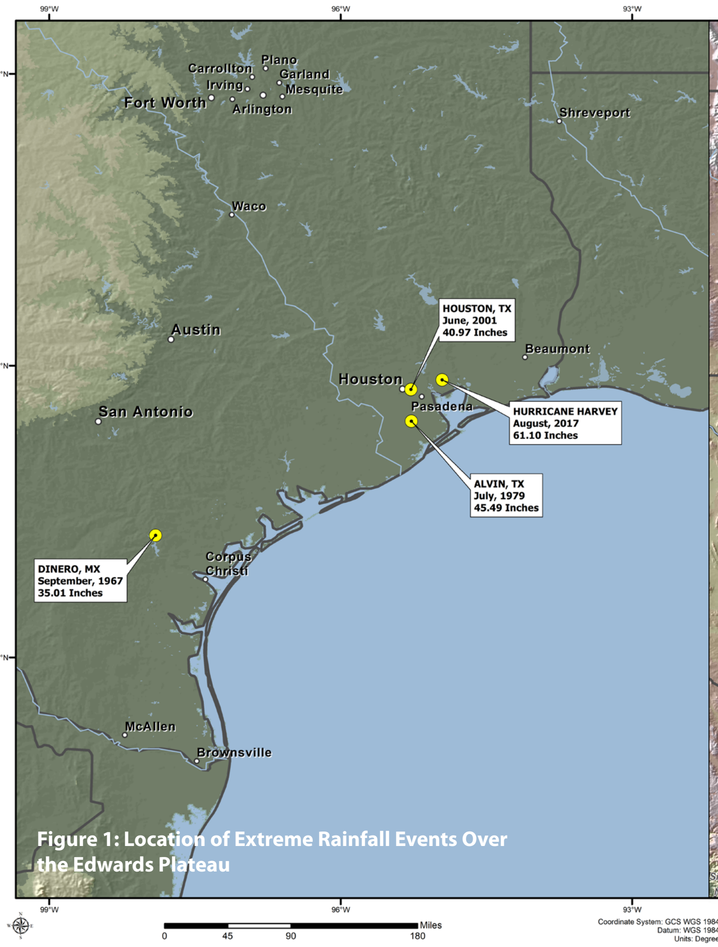


Figure 1: Location of Extreme Rainfall Events Over the Edwards Plateau

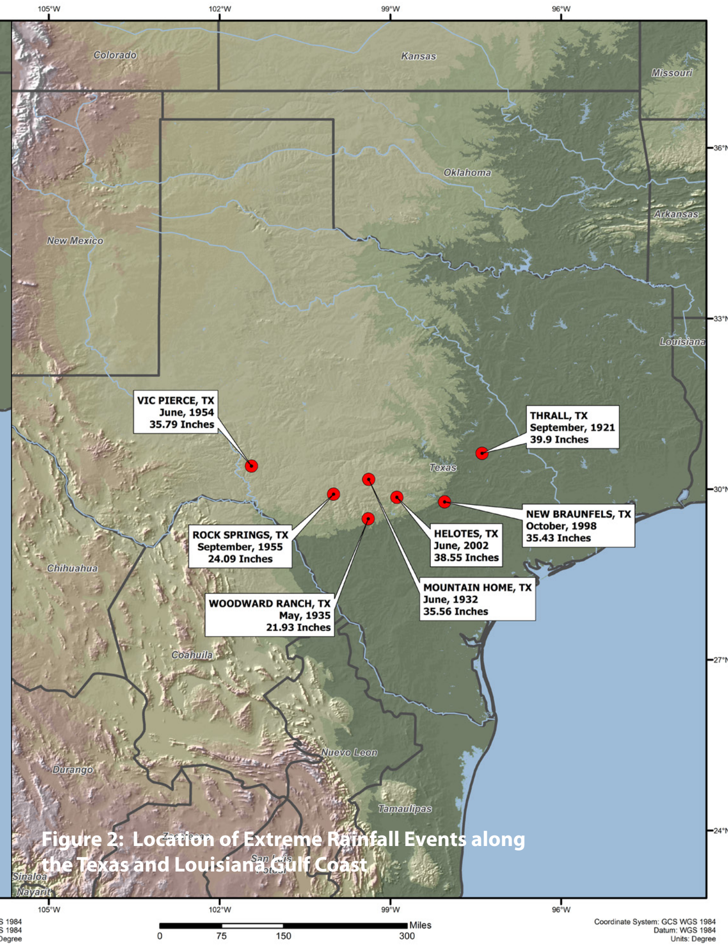


Figure 2: Location of Extreme Rainfall Events along the Texas and Louisiana Gulf Coast

dissipation, as well as resulting flooding impacts have been completed. The focus of this paper is on the rainfall accumulation of the storm and how it compares to PMP and extreme storm analyses that AWA performed between 2014-2016. Refer to the following for more information on the synoptic meteorological environment associated with the storm:

- https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf
- https://www.weather.gov/hgx/hurricaneharvey
- https://weather.com/storms/hurricane/news/tropical-storm-harvey-forecast-texas-louisiana-arkansas;
- American Water Resources Association-Impact (Jan 2018)

## TEXAS COMMISSION ON ENVIRONMENTAL QUALITY BACKGROUND

The Texas Commission on Environmental Quality Dam Safety Program (TCEQ) began monitoring reports from the National Weather Service and from AWA as Hurricane Harvey moved inland to the middle Texas Gulf coast. When the storm slowed and stopped and then moved back toward the Gulf, TCEQ began contacting large dam owners and monitoring owner web sites for flow releases.

TCEQ contacted the owners of 340 dams in the affected storm area by telephone or electronic mail. Only one owner of a high hazard dam reported any damage, that being from spillway erosion. No high hazard dam failed or was reported to overtop. There were four dams that failed, all of which had been exempted from state rules through legislation. An additional 20 dams were found to have slight damage, 11 of which were exempt from state regulation. No major damages were reported from the failures.

Record lake levels and releases occurred at several dams with gated spillways. Many of the small dam owners indicated that large rainfalls occurred at their sites. However, many owners said the April 17-18, 2016 "tax-day" event was more serious than the resulting runoff from Harvey, when more than 17 inches accumulated in a few hours.

Hurricane Harvey and its record rainfalls confirmed the findings of the AWA PMP study, which provides credibility to the state requirements.

## SPAS RAINFALL ANALYSIS

AWA has completed more than 700 rainfall analyses since 2002 using its Storm Precipitation Analysis System (SPAS) (Figure 3). Results of these analyses have been primarily used as input for PMP development, model calibration, model validation, and forensic investigations. The SPAS process has been extensively reviewed and accepted for use in these types of analyses (NRC, 2017). SPAS produces several standard outputs including hourly gridded rainfall


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data, total storm isohyetal maps, depth-area-duration information, annual exceedance probability maps, and mass curve accumulations.

SPAS analyses were completed for all storms used during the Texas PMP study (Figure 4) and therefore provided a consistent and reliable data set from which to make comparisons to the forecast rainfall from Harvey, Harvey rainfall as it was occurring, and the post-analysis investigations. The SPAS database was critical in understanding both the severity of the potential rainfall from the storm before it occurred and communicating how this might compare to the recently updated PMP values, as well as understanding the hardest hit regions.

Forecast rainfall amounts showed the potential for extreme rainfall as much as one week before landfall as seen in Figure 5 (McMahan, 2017). AWA recognized the possibility of extreme rainfall and how it could affect the dam safety community. This was especially relevant in the context that AWA had just completed the development of


**Figure 3: SPAS locations in the United States and Canada where SPAS has been utilized to analyze extreme rainfall events (http://www.appliedweatherassociates.com/spas-storm-analyses.html)**

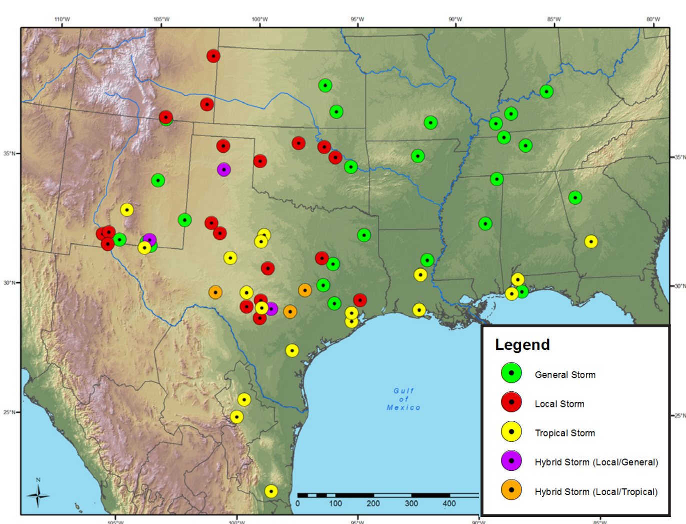


**Figure 4: Storm locations used in the Texas statewide PMP study**

updated PMP values for Texas (Kappel et al., 2016). AWA was in contact with Warren Samuelson at TCEQ before the storm began to affect the region to help with situational awareness. While the storm was occurring, AWA continued communications with TCEQ and others involved in monitoring and analyzing the rainfall. This included the Texas state climatologist and professor at Texas A&M University, Dr. Nielson-Gammon. AWA immediately began an analysis of the rainfall using the SPAS program and worked with Dr. Nielson-Gammon to develop various comparisons of the Harvey rainfall versus previous similar events in order to put the rainfall accumulations in perspective.

The comparisons demonstrated that the Harvey rainfall far exceeded any other observed event, especially for durations greater than 24 hours and area sizes greater than 5,000-square miles, not only in Texas but also in the United States (Figures 6a, 6b, 6c). Figure 7 provides the total storm accumulation pattern resulting from Harvey. Table 1 provides the results of the SPAS rainfall analysis as a depth-area-duration (DAD) table. The DAD provides a 3-dimensional look at the rainfall accumulation both spatially and temporally. Unprecedented amounts of rainfall occurred, with over 60 inches at the storm center during the 5-day period. Even more amazing was the volume of rainfall, with over 20 inches spread over more than 20,000-square miles during the 5-day period. This would be equivalent to more than 25 times the average daily flow through the Mississippi River (Nielson-Gammon, 2017).

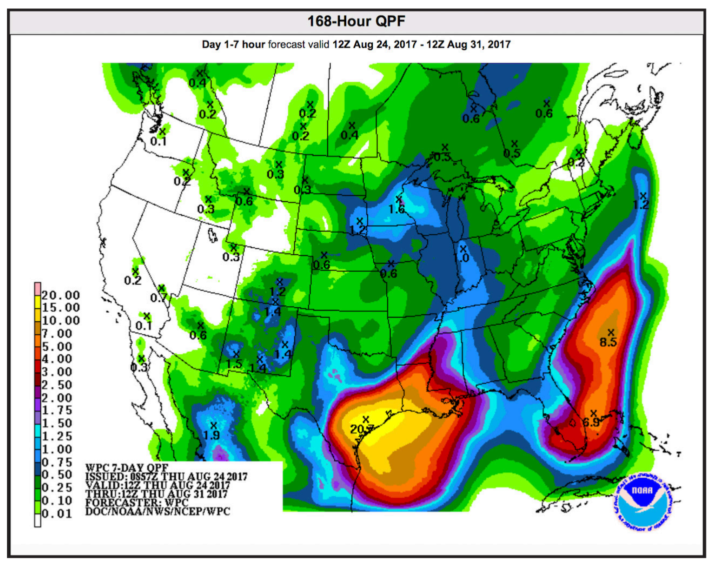


**Figure 5: Quantitative Precipitation Forecast from the Weather Prediction Center for the period August 24, 2017 through August 31, 2017**



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| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
|---|---|---|---|---|
| | **Duration: 48 hours Area: 1000 square miles** | | | |
| 1 | **Harvey 2017** | **30.24** | **1.3** | 2.4% |
| 2 | LA Aug 1940 | 29.53 | 1.3 | |
| 3 | TX Jun 1899 | 27.63 | 1.3 | |
| 4 | Danny 1997 | 25.69 | 1.2 | |
| 5 | Claudette 1979 | 23.97 | 1.1 | |
| | **Duration: 48 hours Area: 5000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **24.52** | **5.5** | 16% |
| 2 | LA Aug 1940 | 21.15 | 4.8 | |
| 3 | TX Jun 1899 | 20.01 | 4.5 | |
| 4 | TX Oct 1994 | 18.60 | 4.2 | |
| 5 | Georges 1998 | 18.33 | 4.2 | |
| | **Duration: 48 hours Area: 10000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **21.37** | **9.7** | 29% |
| 2 | Georges 1998 | 16.62 | 7.5 | |
| 3 | LA Aug 1940 | 16.16 | 7.3 | |
| 4 | TX Jun 1899 | 16.02 | 7.3 | |
| 5 | TX Oct 1994 | 16.00 | 7.3 | |
| | **Duration: 48 hours Area: 20000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **17.59** | **16.0** | 21% |
| 2 | Georges 1998 | 14.58 | 13.2 | |
| 3 | Beulah 1967 | 13.00 | 11.8 | |
| 4 | TX Oct 1994 | 12.46 | 11.3 | |
| 5 | Floyd 1999 | 12.05 | 10.9 | |

**Figure 6a: Comparison of the Hurricane Harvey 48-hour rainfall against similar previous storms and the average daily volume of water flowing through the Mississippi River (mrd)**

| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
|---|---|---|---|---|
| | **Duration: 72 hours Area: 1000 square miles** | | | |
| 1 | **Harvey 2017** | **37.57** | **1.7** | 16% |
| 2 | LA Aug 1940 | 32.51 | 1.5 | |
| 3 | TX Jun 1899 | 31.10 | 1.4 | |
| 4 | Danny 1997 | 27.10 | 1.2 | |
| 5 | Alice 1954 | 26.93 | 1.2 | |
| | **Duration: 72 hours Area: 5000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **30.54** | **7.1** | 26% |
| 2 | TX Jun 1899 | 24.19 | 5.7 | |
| 3 | LA Aug 1940 | 23.63 | 5.4 | |
| 4 | Beulah 1967 | 20.70 | 4.7 | |
| 5 | TX Oct 1994 | 20.15 | 4.6 | |
| | **Duration: 72 hours Area: 10000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **26.28** | **12.2** | 32% |
| 2 | TX Jun 1899 | 19.97 | 9.1 | |
| 3 | Beulah 1967 | 18.50 | 8.4 | |
| 4 | LA Aug 1940 | 17.94 | 8.1 | |
| 5 | TX Oct 1994 | 17.45 | 7.9 | |
| | **Duration: 72 hours Area: 20000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **21.62** | **19.7** | 33% |
| 2 | Beulah 1967 | 16.30 | 14.8 | |
| 3 | TX Jun 1899 | 15.29 | 13.9 | |
| 4 | Georges 1998 | 14.58 | 13.2 | |
| 5 | TX Oct 1994 | 13.92 | 12.6 | |

**Figure 6b: Comparison of the Hurricane Harvey 72-hour rainfall against similar previous storms and the average daily volume of water flowing through the Mississippi River (mrd)**

| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
|---|---|---|---|---|
| | **Duration: 120 hours Area: 1000 square miles** | | | |
| 1 | **Harvey 2017** | **44.73** | **2.1** | 37% |
| 2 | LA Aug 1940 | 32.64 | 1.5 | |
| 3 | TX Jun 1899 | 31.91 | 1.5 | |
| 4 | Claudette 1979 | 27.78 | 1.3 | |
| 5 | Beulah 1967 | 27.20 | 1.2 | |
| | **Duration: 120 hours Area: 5000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **37.73** | **9.0** | 47% |
| 2 | TX Jun 1899 | 25.60 | 5.8 | |
| 3 | LA Aug 1940 | 23.93 | 5.4 | |
| 4 | Beulah 1967 | 22.40 | 5.1 | |
| 5 | TX Oct 1994 | 20.86 | 4.7 | |
| | **Duration: 120 hours Area: 10000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **32.83** | **15.7** | 53% |
| 2 | TX Jun 1899 | 21.39 | 9.7 | |
| 3 | Beulah 1967 | 20.50 | 9.3 | |
| 4 | LA Aug 1940 | 18.37 | 8.3 | |
| 5 | TX Oct 1994 | 18.06 | 8.2 | |
| | **Duration: 120 hours Area: 20000 square miles** | | | |
| Rank | Event | Average (in) | Amount (mrd) | % over previous record |
| 1 | **Harvey 2017** | **27.36** | **25.6** | 46% |
| 2 | Beulah 1967 | 18.70 | 17.0 | |
| 3 | TX Jun 1899 | 17.02 | 15.4 | |
| 4 | Georges 1998 | 15.71 | 14.3 | |
| 5 | NC Sep 2010 | 14.83 | 13.4 | |

**Figure 6c: Comparison of the Hurricane Harvey 120-hour rainfall against similar previous storms and the average daily volume of water flowing through the Mississippi River (mrd)**

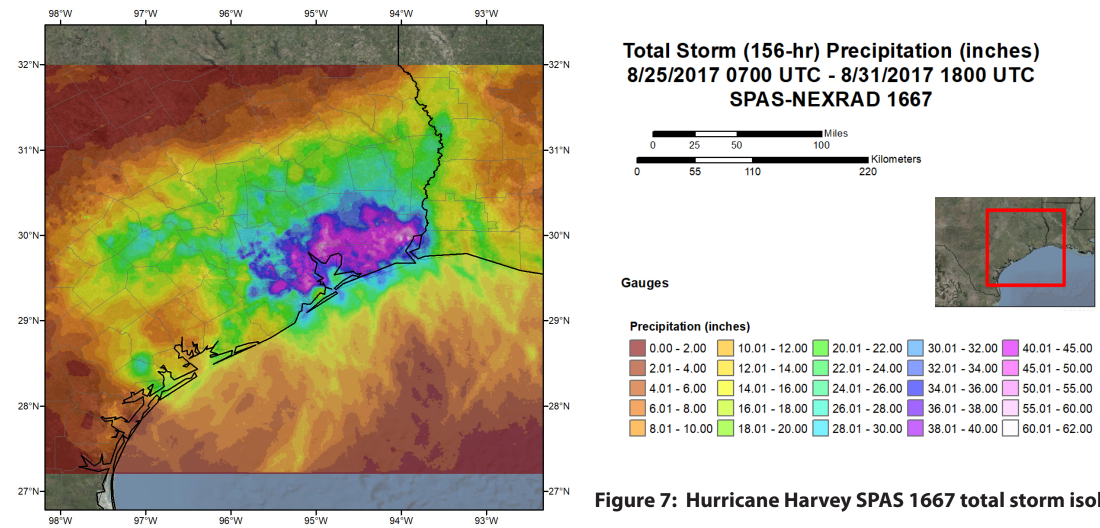


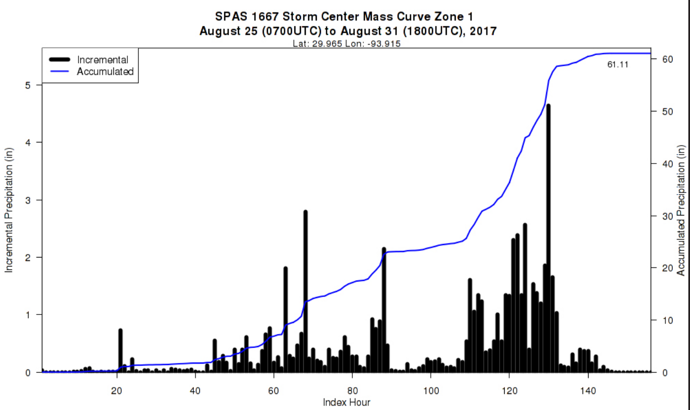

**Figure 7: Hurricane Harvey SPAS 1667 total storm isohyetal**

**Table 1: Hurricane Harvey depth-area-duration table**

| Storm 1667 - August 25 (0700 UTC) - August 31 (1800 UTC), 2017<br>MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Area ($mi^2$) | Duration (hours) | | | | | | | | | | | | | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 12 | 18 | 24 | 36 | 48 | 72 | 96 | 120 | Total |
| 0.4 | 5.80 | 11.47 | 14.56 | 17.08 | 18.76 | 19.93 | 23.92 | 28.16 | 34.52 | 37.39 | 40.95 | 51.84 | 58.62 | 60.25 | 61.11 |
| 1 | 5.64 | 11.18 | 14.38 | 16.94 | 18.63 | 19.76 | 23.67 | 27.88 | 34.19 | 37.04 | 40.61 | 51.48 | 58.23 | 59.78 | 60.62 |
| 10 | 5.40 | 10.04 | 13.25 | 16.48 | 18.28 | 18.98 | 22.68 | 26.86 | 32.72 | 35.34 | 39.07 | 49.43 | 55.91 | 57.53 | 58.36 |
| 25 | 5.07 | 9.37 | 12.68 | 15.99 | 18.03 | 18.85 | 22.11 | 26.19 | 31.60 | 34.18 | 37.64 | 47.20 | 53.09 | 55.15 | 56.06 |
| 50 | 4.90 | 8.84 | 12.27 | 15.46 | 17.68 | 18.47 | 21.37 | 25.35 | 30.62 | 33.17 | 36.49 | 45.49 | 51.16 | 53.37 | 54.31 |
| 100 | 4.65 | 8.25 | 11.71 | 14.64 | 17.01 | 17.79 | 20.29 | 24.09 | 28.98 | 31.40 | 35.93 | 43.68 | 49.29 | 51.66 | 52.67 |
| 150 | 4.45 | 7.92 | 11.20 | 13.98 | 16.34 | 17.13 | 19.64 | 23.56 | 27.45 | 29.59 | 35.19 | 42.85 | 48.01 | 50.68 | 51.73 |
| 200 | 4.28 | 7.67 | 10.77 | 13.46 | 15.73 | 16.58 | 19.12 | 23.06 | 26.81 | 28.97 | 34.57 | 42.27 | 47.04 | 49.83 | 51.01 |
| 300 | 4.03 | 7.24 | 10.09 | 12.64 | 14.74 | 15.67 | 18.35 | 22.22 | 25.81 | 28.13 | 33.54 | 41.28 | 45.90 | 48.66 | 49.86 |
| 400 | 3.81 | 6.95 | 9.54 | 11.94 | 13.99 | 14.91 | 17.71 | 21.52 | 24.98 | 27.55 | 32.75 | 40.47 | 45.10 | 47.75 | 49.06 |
| 500 | 3.63 | 6.61 | 9.08 | 11.39 | 13.27 | 14.22 | 17.14 | 20.88 | 24.18 | 27.07 | 32.15 | 39.80 | 44.50 | 47.01 | 48.34 |
| 1000 | 2.96 | 5.40 | 7.36 | 9.23 | 10.76 | 11.88 | 15.42 | 18.81 | 21.34 | 25.41 | 30.24 | 37.57 | 42.27 | 44.73 | 46.03 |
| 2000 | 2.30 | 4.00 | 5.87 | 7.24 | 8.55 | 9.57 | 13.40 | 16.53 | 18.70 | 23.35 | 27.98 | 34.95 | 39.66 | 42.23 | 43.44 |
| 3500 | 1.84 | 3.25 | 4.73 | 5.87 | 6.89 | 7.81 | 11.57 | 14.43 | 16.90 | 21.31 | 25.92 | 32.49 | 37.11 | 39.84 | 40.82 |
| 5000 | 1.57 | 2.82 | 4.03 | 5.06 | 5.98 | 6.82 | 10.33 | 13.10 | 15.65 | 19.87 | 24.52 | 30.54 | 35.04 | 37.73 | 38.71 |
| 7500 | 1.30 | 2.33 | 3.34 | 4.22 | 5.02 | 5.76 | 9.10 | 11.62 | 14.17 | 18.23 | 22.77 | 28.04 | 32.38 | 35.09 | 35.94 |
| 10000 | 1.14 | 2.04 | 2.92 | 3.71 | 4.43 | 5.08 | 8.23 | 10.59 | 13.06 | 17.01 | 21.37 | 26.28 | 30.36 | 32.83 | 33.77 |
| 15000 | 0.88 | 1.67 | 2.39 | 3.10 | 3.73 | 4.26 | 7.04 | 9.18 | 11.45 | 15.26 | 19.19 | 23.53 | 27.29 | 29.79 | 30.56 |
| 20000 | 0.73 | 1.37 | 1.99 | 2.59 | 3.15 | 3.63 | 6.13 | 8.16 | 10.29 | 13.90 | 17.59 | 21.62 | 25.09 | 27.36 | 28.23 |
| 35000 | 0.51 | 0.93 | 1.37 | 1.80 | 2.21 | 2.56 | 4.57 | 6.21 | 7.76 | 10.76 | 13.74 | 17.48 | 20.44 | 22.59 | 23.54 |
| 50000 | 0.39 | 0.70 | 1.03 | 1.37 | 1.68 | 1.96 | 3.52 | 4.94 | 6.28 | 8.93 | 11.31 | 14.62 | 17.14 | 19.33 | 20.46 |
| 75000 | 0.26 | 0.52 | 0.74 | 1.02 | 1.28 | 1.45 | 2.65 | 3.65 | 4.60 | 6.68 | 8.58 | 11.65 | 13.75 | 15.53 | 16.60 |
| 100000 | 0.20 | 0.40 | 0.59 | 0.81 | 0.99 | 1.17 | 2.17 | 2.95 | 3.70 | 5.36 | 6.85 | 9.34 | 11.03 | 12.43 | 13.44 |
| 120162 | 0.17 | 0.34 | 0.51 | 0.67 | 0.83 | 0.99 | 1.86 | 2.56 | 3.19 | 4.64 | 5.94 | 8.08 | 9.56 | 10.77 | 11.65 |

The rainfall accumulation pattern produced a similar footprint as seen in previous storms in the region (Figure 8). The heaviest rainfall was centered just inland from the coast, where coastal convergence processes maximized the rainfall production. Also noteworthy was the accumulation pattern through time with the heavy rainfall occurring over long time periods covering several days (Table 2). The extreme rainfall, which occurred over several days, resulted in daily rainfall records that were set at the Houston Intercontinental Airport official observation site (KIAH). At this location, Harvey produced the greatest daily amount on August 27th and 5th greatest daily amount on August 26th (Figure 9).

**Table 2: Hurricane Harvey rainfall accumulation through time at the storm center location covering the period from August 25 0700UTC through August 31 1800UTC**




## COMPARISON TO PREVIOUS STORMS

As discussed previously, the storm location and overall pattern were similar to previous tropical rainfall events in the region. In June 2001, Hurricane Allison produced devastating flooding in the Houston region, with over 40 inches of rainfall occurring in 24 hours. This storm spatial coverage was similar to Harvey (Figure 10). However, the rainfall from Allison only lasted a little over a day.

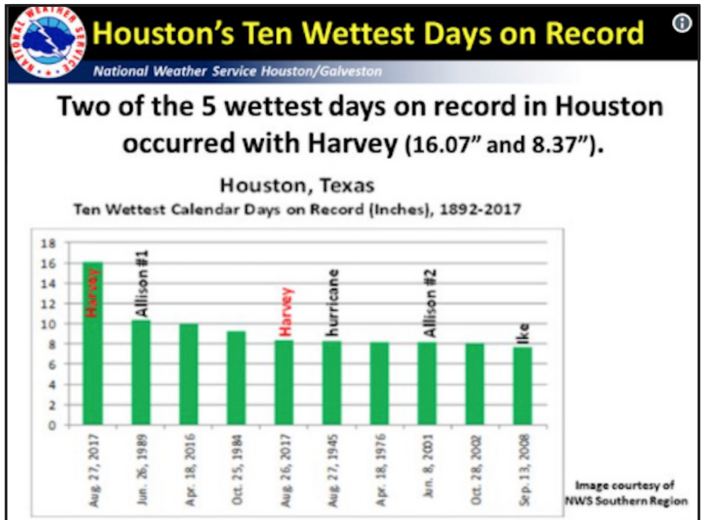



**Figure 9: Daily rainfall records at the Houston official observation site (KIAH)**

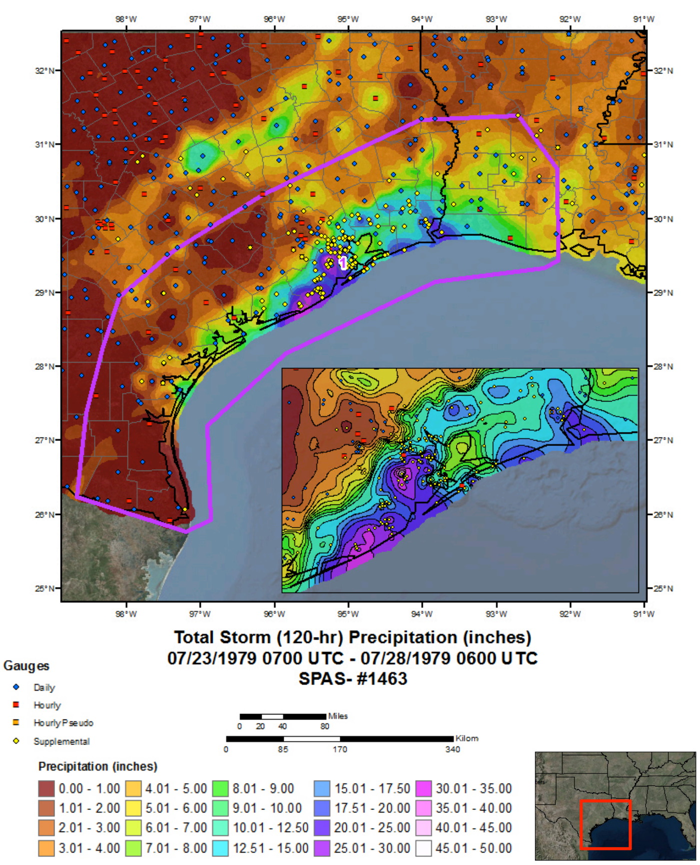



**Figure 8: SPAS 1463, Alvin July 1979 total storm isohyetal**

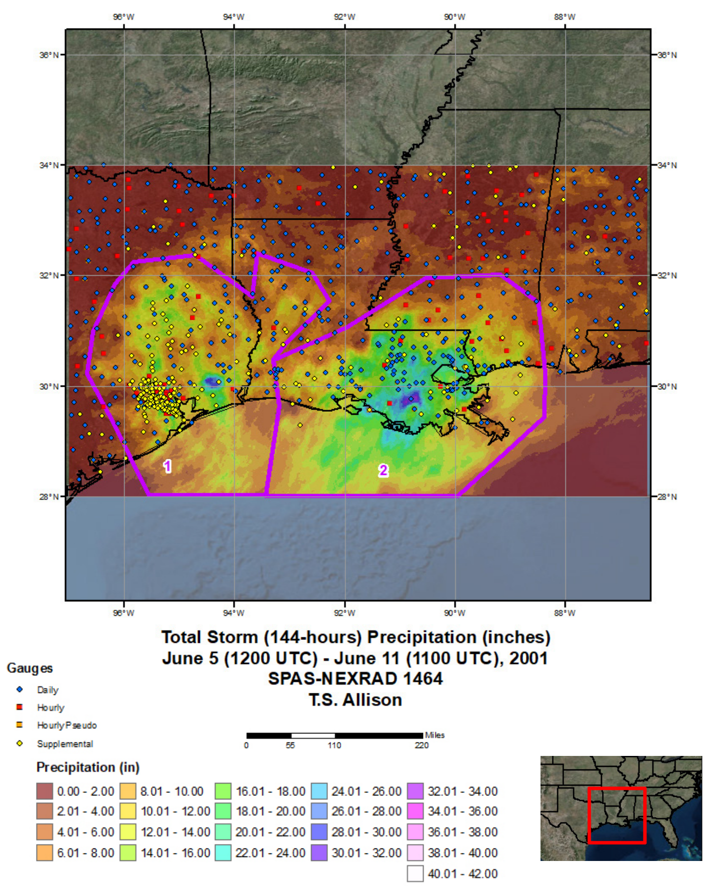



**Figure 10: SPAS 1464, Allison June 2001 total storm isohyetal**



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**Table 3: SPAS 1464, Allison June 2001 depth-area-duration table**

| Storm 1464 Zone 1 - June 5 (1200 UTC) - June 11 (1100 UTC), 2001 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES) | | | | | | | | | | | | | |
| | Duration (hours) | | | | | | | | | | | | |
| **areasqmi** | 1 | 3 | 6 | 12 | 18 | 24 | 36 | 48 | 72 | 96 | 120 | 144 | Total |
| **0.4** | 6.28 | 14.09 | 20.98 | 29.17 | 29.39 | 29.41 | 29.53 | 29.71 | 29.89 | 40.56 | 40.74 | 40.97 | 29.53 |
| **1** | 6.25 | 14.04 | 20.92 | 29.06 | 29.29 | 29.32 | 29.42 | 29.61 | 29.77 | 40.42 | 40.61 | 40.82 | 29.42 |
| **10** | 5.74 | 13.31 | 19.95 | 27.88 | 27.99 | 28.01 | 28.27 | 28.27 | 28.52 | 38.35 | 38.61 | 39.15 | 28.27 |
| **25** | 5.40 | 12.14 | 18.05 | 26.73 | 27.10 | 27.13 | 27.16 | 27.30 | 27.69 | 36.99 | 37.20 | 37.68 | 27.16 |
| **50** | 5.26 | 11.36 | 16.04 | 24.27 | 25.21 | 25.25 | 25.30 | 25.48 | 26.23 | 35.42 | 35.79 | 35.92 | 25.30 |
| **100** | 5.07 | 10.32 | 13.61 | 20.46 | 20.59 | 20.63 | 20.64 | 22.57 | 24.69 | 31.77 | 32.87 | 33.10 | 20.64 |
| **150** | 4.88 | 8.64 | 13.06 | 19.42 | 19.68 | 19.75 | 19.81 | 20.33 | 24.23 | 29.38 | 31.06 | 31.81 | 19.81 |
| **200** | 4.68 | 8.52 | 12.39 | 17.42 | 17.53 | 17.53 | 17.81 | 19.02 | 23.85 | 27.91 | 30.03 | 30.61 | 17.81 |
| **300** | 4.32 | 7.86 | 11.57 | 16.44 | 16.67 | 16.67 | 16.69 | 17.84 | 22.75 | 25.49 | 28.83 | 29.05 | 16.69 |
| **400** | 4.04 | 7.19 | 10.70 | 15.46 | 15.80 | 15.86 | 15.95 | 16.57 | 21.71 | 24.68 | 27.79 | 27.99 | 15.95 |
| **500** | 3.79 | 7.12 | 9.54 | 14.15 | 15.08 | 15.12 | 15.24 | 15.31 | 20.48 | 24.12 | 26.73 | 26.94 | 15.24 |
| **1,000** | 2.73 | 5.71 | 7.70 | 12.12 | 12.31 | 12.38 | 12.41 | 14.15 | 18.18 | 21.11 | 23.91 | 24.15 | 12.41 |
| **2,000** | 2.08 | 3.92 | 6.06 | 9.63 | 9.80 | 9.80 | 9.91 | 11.98 | 14.03 | 15.84 | 17.45 | 20.85 | 9.91 |
| **5,000** | 1.61 | 2.70 | 4.24 | 5.65 | 5.87 | 7.74 | 8.56 | 9.37 | 11.81 | 15.57 | 15.90 | 17.88 | 8.56 |
| **10,000** | 0.51 | 1.46 | 2.47 | 4.77 | 5.57 | 5.61 | 6.85 | 8.21 | 10.50 | 12.41 | 12.79 | 15.29 | 6.85 |
| **20,000** | 0.38 | 0.92 | 1.40 | 2.73 | 3.48 | 4.40 | 5.59 | 6.58 | 8.81 | 10.59 | 12.07 | 13.01 | 5.59 |
| **50,000** | 0.24 | 0.51 | 0.95 | 1.56 | 2.14 | 2.59 | 3.25 | 4.40 | 5.93 | 7.64 | 9.11 | 9.24 | 3.25 |
| **54,778** | 0.23 | 0.50 | 0.90 | 1.54 | 2.10 | 2.43 | 3.16 | 4.39 | 5.82 | 7.62 | 8.59 | 8.70 | 3.16 |

**Table 4: SPAS 1463, Alvin July 1979 depth-area-duration table**

| Storm 1463 Zone 1 - July 23 (0700 UTC) - July 28 (0600 UTC), 1979 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES) | | | | | | | | | | | | |
| | Duration (hours) | | | | | | | | | | | |
| **areasqmi** | 1 | 3 | 6 | 12 | 18 | 24 | 36 | 48 | 72 | 96 | 120 | Total |
| **0.4** | 6.46 | 13.79 | 20.52 | 32.51 | 39.79 | 43.08 | 45.46 | 45.47 | 45.48 | 45.49 | 45.49 | 45.49 |
| **1** | 6.45 | 13.75 | 20.47 | 32.37 | 39.61 | 42.88 | 45.24 | 45.24 | 45.27 | 45.28 | 45.28 | 45.28 |
| **10** | 6.26 | 13.36 | 19.88 | 30.47 | 36.90 | 40.15 | 42.25 | 42.31 | 42.39 | 42.39 | 42.44 | 42.44 |
| **25** | 6.09 | 12.97 | 19.41 | 27.97 | 33.82 | 35.34 | 37.29 | 37.61 | 37.61 | 38.37 | 38.54 | 38.54 |
| **50** | 5.89 | 12.75 | 18.87 | 25.26 | 31.40 | 32.67 | 34.06 | 34.06 | 34.06 | 35.59 | 35.78 | 35.78 |
| **100** | 5.60 | 12.24 | 18.06 | 23.89 | 28.14 | 30.20 | 31.27 | 31.30 | 31.57 | 32.81 | 35.23 | 35.23 |
| **150** | 5.40 | 11.82 | 17.46 | 22.77 | 27.53 | 28.61 | 28.61 | 29.89 | 30.69 | 30.71 | 34.68 | 34.68 |
| **200** | 5.22 | 11.44 | 16.92 | 21.72 | 26.10 | 27.27 | 27.80 | 27.85 | 30.01 | 30.41 | 34.13 | 34.13 |
| **300** | 4.89 | 10.70 | 15.85 | 20.55 | 24.89 | 25.60 | 26.56 | 26.99 | 29.39 | 30.26 | 33.03 | 33.03 |
| **400** | 4.58 | 9.99 | 14.65 | 18.73 | 22.62 | 22.62 | 22.62 | 26.21 | 28.92 | 30.12 | 31.94 | 31.94 |
| **500** | 4.28 | 9.38 | 13.53 | 17.75 | 21.71 | 22.08 | 22.41 | 25.41 | 28.48 | 29.97 | 30.84 | 30.84 |
| **1,000** | 3.52 | 7.61 | 9.64 | 14.52 | 17.83 | 20.48 | 21.95 | 23.89 | 26.35 | 27.69 | 27.85 | 27.85 |
| **2,000** | 2.48 | 5.87 | 8.09 | 11.33 | 13.74 | 16.14 | 19.00 | 19.18 | 22.03 | 24.35 | 24.51 | 24.51 |
| **5,000** | 1.71 | 2.65 | 5.10 | 7.63 | 9.24 | 12.10 | 14.33 | 15.27 | 15.40 | 19.07 | 19.16 | 19.16 |
| **10,000** | 0.51 | 1.33 | 2.22 | 5.06 | 7.06 | 8.95 | 10.55 | 10.69 | 11.55 | 14.87 | 14.95 | 14.95 |
| **20,000** | 0.30 | 0.77 | 1.61 | 2.31 | 2.82 | 4.82 | 4.82 | 5.62 | 9.71 | 10.62 | 10.81 | 10.81 |
| **50,000** | 0.24 | 0.51 | 0.87 | 1.54 | 2.08 | 2.56 | 3.60 | 4.29 | 4.74 | 5.72 | 5.77 | 5.77 |
| **54,778** | 0.24 | 0.50 | 0.82 | 1.51 | 2.04 | 2.55 | 3.47 | 3.98 | 4.72 | 5.10 | 5.15 | 5.15 |

This resulted in total storm rainfall amounts and volumes that were much smaller than Harvey (Table 3). Prior to Allison was Alvin in 1979. Again, this tropical system produced extreme rainfall over the Houston area, with more than 40 inches in 24 hours in some locations (see Figure 8). But like Allison, Alvin did not last more than 30 hours (Table 4). Each of these storms were similar regarding storm type and location, but the total rainfall amounts and spatial coverage were limited by overall duration.

## MAXIMIZATION OF HURRICANE HARVEY

Most important for TCEQ and the dam safety community in general was whether Harvey exceeded PMP estimates. This is because high hazard structures are designed to the Probable Maximum Flood (PMF). The PMF is a direct result of the PMP, therefore if PMP design values are exceeded, there is a possibility that high hazard structures can be compromised.

PMP is developed by analyzing actual storm events, then maximizing those storms in-place, transpositioning those storms to locations of interest, and combining the results to produce a worst-case scenario. AWA had already done this with numerous storms as part of the Texas statewide PMP study (Figure 4) and therefore had a readily available data set to compare to Harvey values.

**Table 5: In-place maximization calculations**

| | | | |
|---|---|---|---|
| Storm Name: | SPAS 1667 - Hurricane Harvey | Storm Adjustments | |
| Storm Date: | August 25-31, 2017 | | |
| AWA Analysis Date: | 8/1/18 | | |
| Temporal Transposition Date | 0-Jan | | |

| | Lat | Long |
|---|---|---|
| Storm Center Location | 29.97 N | 93.92W |
| Storm Rep SST Location | 27.00 N | 93.00 W |

| | | |
|---|---|---|
| Moisture Inflow Direction | SSE @ 215 | miles |
| Storm Center Elevation | 30 | feet |
| Storm Analysis Duration | 24 | hours |

| | | | | | | |
|---|---|---|---|---|---|---|
| The storm representative SST is | 86.0 | with total precipitable water above sea level of | | | 4.67 | inches |
| The in-place maximum SST is | 87.0 | with total precipitable water above sea level of | | | 4.86 | inches |
| The in-place storm elevation is | 30 | feet which subtracts | 0.01 | inches of precipitable water at | 86.0 | |
| The in-place storm elevation is | 30 | which subtracts | 0.01 | inches of precipitable water at | 87.0 | |

The in-place maximization factor is 1.04

Storm rep SST value based on daily SST values Aug 28-29. Heaviest rainfall period at storm center occurred from Aug 29-30. HYSPLIT from Aug 29 12Z used as guidance for storm rep location. This showed inflow from the warm GOF water in the Bay of Campeche region and likely one of the reasons the second rainall burst occurred.

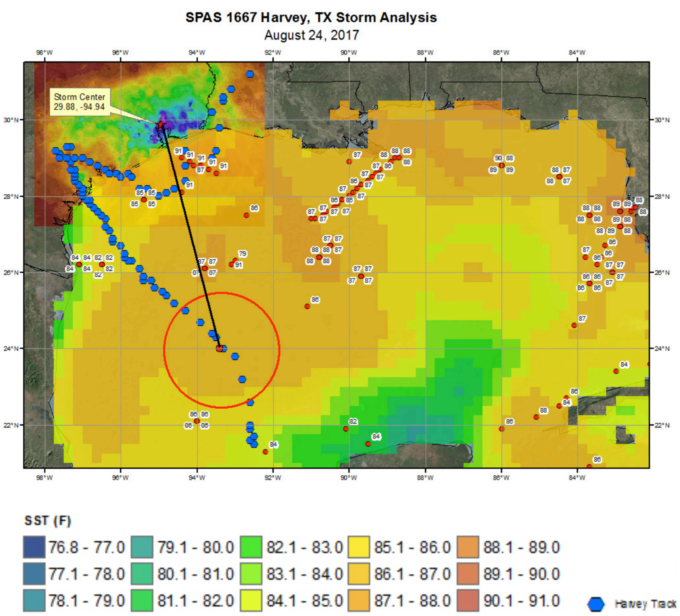


**Figure 11: In-place maximization analysis**

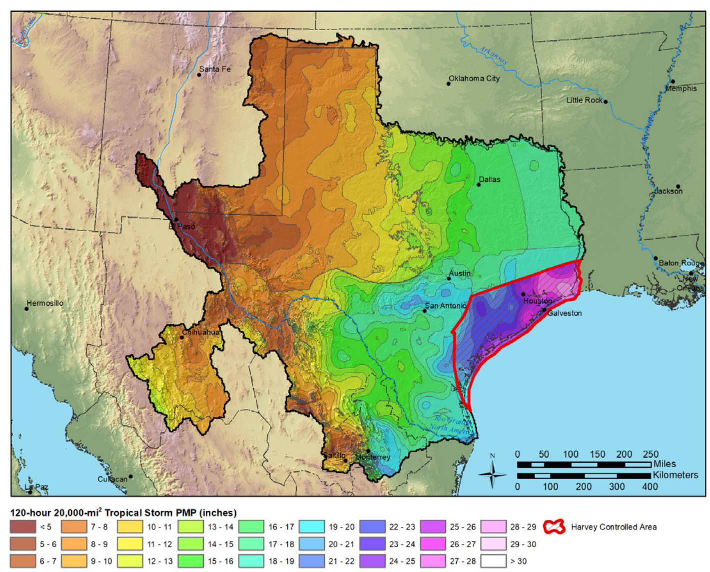


**Figure 12: Region where tropical storm PMP values increased after Hurricane Harvey for 120-hours and 20,000-square miles**

**Table 6: Comparison of PMP to maximized Harvey rainfall**

| | # of Grid Points Controlled by Harvey | Average Tropical PMP (post-Harvey) | Average Tropical PMP (pre-Harvey) | Average % Increase | Average General PMP (pre-Harvey) | Average % Increase over General PMP | Average HMR 51 PMP | Average % Increase from HMR 51 |
|---|---|---|---|---|---|---|---|---|
| 5,000-sqmi 48-hour | 485 | 25.8" | 25.4" | 1.6% | 31.7" | No Increase | - | No Increase |
| 5,000-sqmi 72-hour | 4,566 | 30.1" | 27.4" | 9.9% | 35.3" | No Increase | 31.1" | No Increase |
| 5,000-sqmi 96-hour | 9,785 | 31.5" | N/A | N/A | N/A | - | N/A | No Increase |
| 5,000-sqmi 120-hour | 9,785 | 33.9" | N/A | N/A | N/A | - | N/A | No Increase |
| 10,000-sqmi 48-hour | 1,668 | 22.0" | 21.1" | 4.0% | 24.7" | No Increase | 22.9" | No Increase |
| 10,000-sqmi 72-hour | 4,736 | 25.9" | 23.4" | 10.7% | 29.1" | No Increase | 26.8" | No Increase |
| 10,000-sqmi 96-hour | 9,785 | 27.3" | 23.6" | 15.7% | 28.2" | No Increase | N/A | No Increase |
| 10,000-sqmi 120-hour | 9,785 | 29.5" | 23.8" | 24.0% | 28.4" | No Increase | N/A | No Increase |
| 20,000-sqmi 48-hour | 4,009 | 17.4" | 16.2" | 7.3% | 20.6" | No Increase | 22.8" | No Increase |
| 20,000-sqmi 72-hour | 6,167 | 20.8" | 18.4" | 12.5% | 22.0" | No Increase | 26.8" | No Increase |
| 20,000-sqmi 96-hour | 7,714 | 23.4" | 20.6" | 13.8% | 23.1" | **1.5%** | N/A | No Increase |
| 20,000-sqmi 120-hour | 9,566 | 24.7" | 20.7" | 18.9% | 22.8" | **8.4%** | N/A | No Increase |


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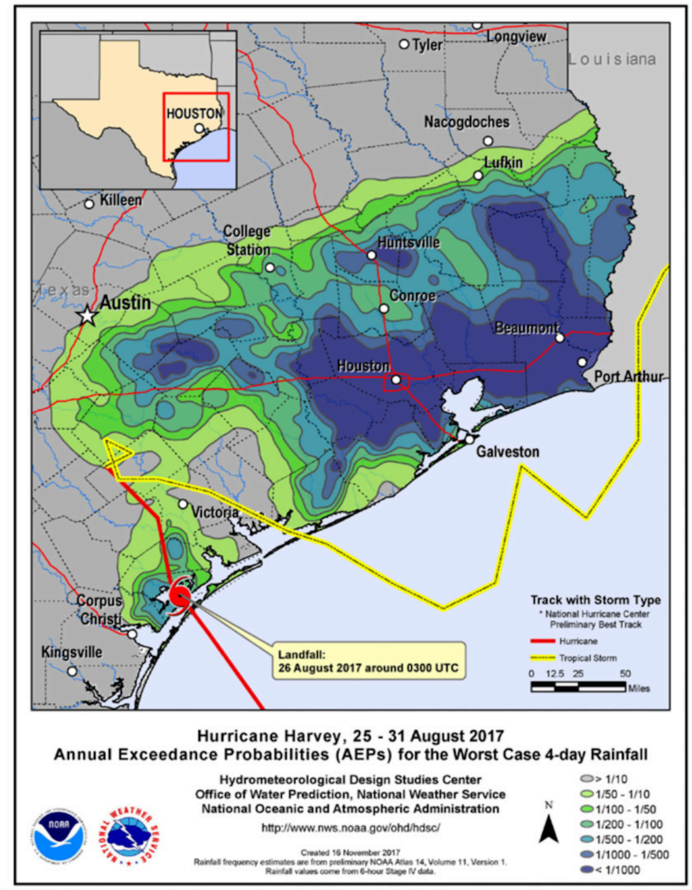


**Figure 13: Annual Exceedance Probability of the Hurricane Harvey rainfall compared to NOAA Atlas 14 values**

As soon as the preliminary SPAS analysis of Harvey was completed, AWA began the in-place maximization process. Harvey was nearly at the maximum amount of moisture that the atmosphere could provide, with a resulting in-place maximization factor of only 1.02 (i.e. a 2% increase). Figure 11 and Table 5 provide the in-place maximization factor analysis results. This shows that the storm could only have been 2% larger than observed had the maximum amount of atmospheric moisture been available to the storm versus what was observed. This is about as small of an increase as is possible, and of the hundreds of storms AWA has maximized over the years, only a few have achieved this. Examples include the world-record rainfall associated with the Smethport, PA July 1942 storm and the Hale, CO May 1935 storm. Each of these storms is very important for setting levels of PMP where they occurred.

## COMP ARISON TO PREVIOUS PMP AND PRECIPITATION FREQUENCY ESTIMATES

Once Harvey was maximized, AWA was able to complete direct comparisons to the recently concluded Texas statewide PMP, as well as previous HMR 51 PMP values. The results of these comparisons demonstrated that Harvey was significantly larger than the previous tropical storm PMP values in the region (Figure 12). However, Harvey did not exceed the overall PMP values for the region when all storm types were considered, with two minor exceptions. At 96 hours 20,000-square miles and 120 hours 20,000-square miles, Harvey was 0.6% greater and 4.4% greater, respectively (Table 6). Unfortunately, HMR 51 PMP values only extend to 72 hours, so similar comparisons to those values were not possible. This also demonstrates one of the problems with HMR 51 in that it does not provide PMP values at all required area sizes and durations for regions of the country where storms last longer than 72 hours, like the Texas coastal region.

The storm far exceeded the NOAA Atlas 14 precipitation frequency values, with a large region experiencing greater than a 1,000-year recurrence interval (Figure 13). Preliminary investigations demonstrate that the rainfall accumulations were likely somewhere between a $10^{-5}$ and $10^{-6}$ recurrence interval.

## SUMMARY

Harvey was a real-world example of a PMP rainfall event and demonstrated that PMP can happen. One very important outcome for the dam safety community is that even with Harvey producing PMP-level rainfall, no high hazard dam failed in Texas or Louisiana. This is likely the result of good dam safety practices and design, as well as luck. Therefore, it is extremely important that the dam safety community follows standard practice in design of structures, monitoring of structures, and applying the most up-to-date science and data.

Harvey also demonstrates the need to continually update the storm database and PMP estimates as new storms occur and the understanding of extreme rainfall mechanisms increases. Programs should be in place that allow for updating of these databases and PMP values in real time as events occur. TCEQ dam safety, National Weather Service, members of the academic community, and private consultants should all be commended for their monitoring, communication, and response prior to, during, and after Harvey. This type of coordination and communication should become the standard for other state dam safety and federal dam safety offices because these types of events will occur again.

## REFERENCES

Kappel, W.D., Hultstrand, D.M., Muhlestein, G.A., Steinhilber, K., McGlone, D., Parzybok, T.W., and B. Lawrence, September 2016: Statewide Probable Maximum Precipitation for Texas. Prepared for the Texas Commission of Environmental Quality.

McMahon, Personal Communication, August 2017

Nielson-Gammon, Personal Communication, September 2017

Nuclear Regulatory Commission, January 2017: Commercial Grade Dedication and Audit of SPAS, ENERCON Appendix B Program.

World Meteorological Organization, 2009: Manual for Estimation of Probable Maximum Precipitation, No. 1045, WMO, Geneva, 259 pp.

**Bill Kappel**
President/Chief Meteorologist
Applied Weather Associates
PO Box 175
Monument, CO 80132
(719) 964-3395
billkappel@appliedweatherassociates.com

Bill Kappel is president and chief meteorologist of Applied Weather Associates. Mr. Kappel has been the project manager and technical lead for more than 100 probable maximum precipitation studies over the last 15 years covering just about every meteorological setting possible. Mr. Kappel has also been involved in more than 700 storm analyses using the Storm Precipitation Analysis System (SPAS) since 2002. These results have been used to calculate PMP values, used for model calibration, in forensic meteorological investigations, and various climatological and precipitation frequency analyses. Prior to joining AWA, Mr. Kappel was an on-air meteorologist at several TV stations across the country.

**Doug Hultstrand**
Senior Hydrometeorologist
Applied Weather Associates
PO Box 175
Monument, CO 80132
(720) 771-5840
dhultstrand@appliedweatherassociates.com

Doug Hultstrand is a senior hydrometeorologist at Applied Weather Associates, where he has been involved in all aspects of sPMP development, storm analyses, and forensic meteorological investigations. Mr. Hultstrand received a bachelor's degree from the University of Colorado at Boulder (physical geography, and hydrology certificate), a Master of Science degree from Colorado State University (watershed science), and is currently completing a doctoral degree in earth sciences at Colorado State University. Mr. Hultstrand has worked with U.S. Geological Survey (USGS) Alpine Hydrology Research Group (AHRG), the Institute of Arctic and Alpine Research (INSTAAR), and the U.S. Forest Service Rocky Mountain Research Station (RMRS).




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