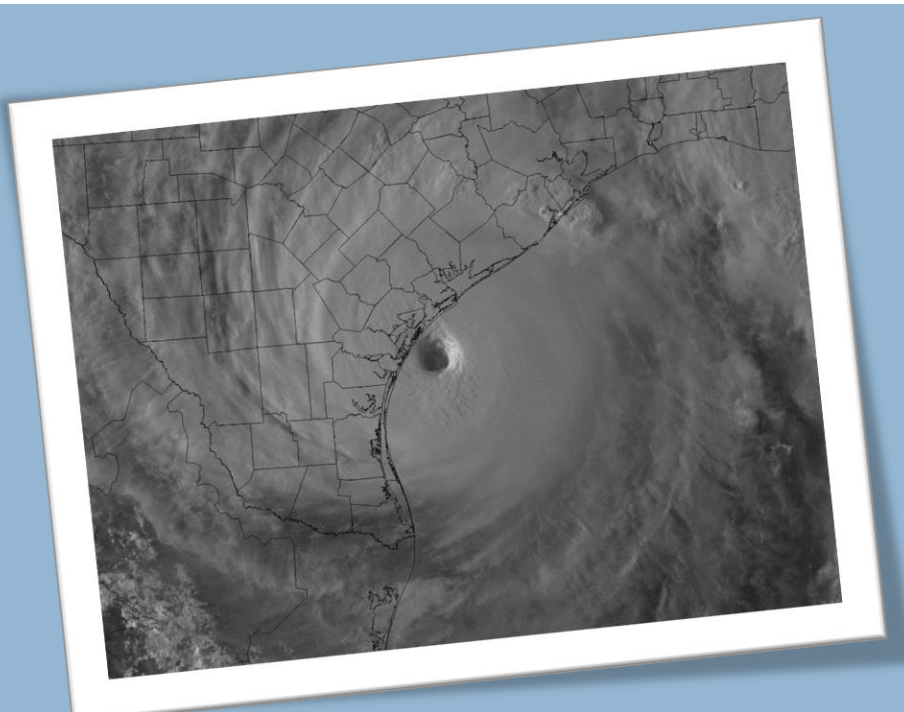
HURRICANE HARVEY: PRECIPITATION AND FLOOD ANALYSIS IN THE LAKE HOUSTON AREA



Indu Venu Sabaraya

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ABSTRACT

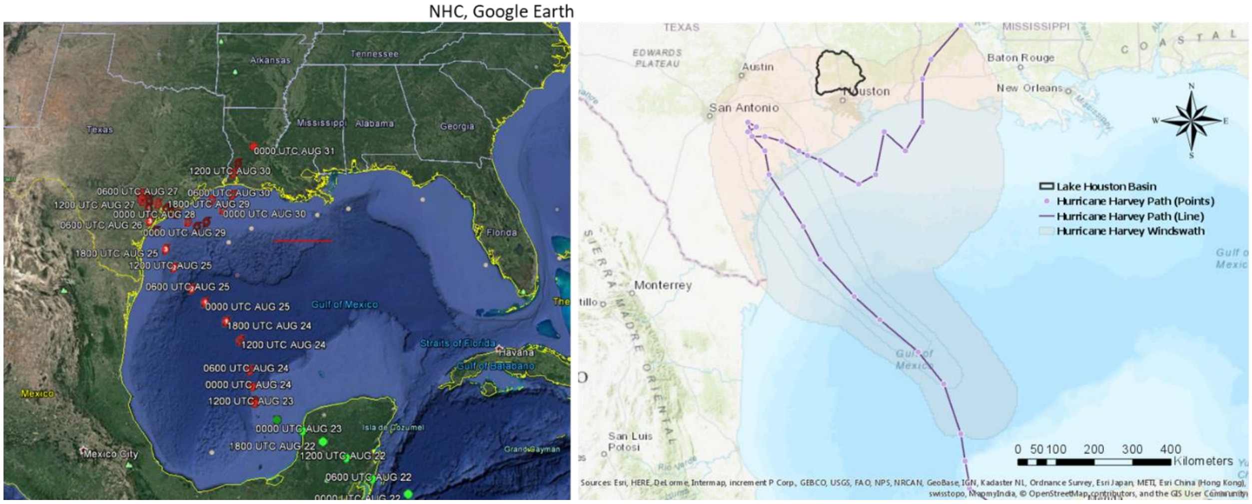
When Hurricane Harvey made landfall near Rockport, TX on August 25, 2017, it became the nation's first major (Category 3 or stronger) hurricane since Hurricane Wilma.[1] Catastrophic flooding was caused by the slow moving system with a gauge near Cedar Bayou, Texas, measuring 51.88 inches of rainfall, a record amount in the continental United States.[2] On August 28, Houston Mayor Sylvester Turner announced that water influx to Lake Houston caused the submersion of a water treatment plant north-east of the city.[3] It was reported that 65 separate releases from waste water treatment plants in Harris county released over 20 million gallons of untreated sewage into the area.[4] Flooding in the area around Lake Houston, which hosts a variety of economic activity and ranches, may cause a high loading of nitrogen, phosphorous and organic matter to flow into Lake Houston.

The objective of this term paper will be to assess flood levels and the impact of Hurricane Harvey on water quality parameters like total phosphorous and total nitrogen in the Lake Houston area. These parameters are influenced by point- as well as non-point sources and was greatly affected by releases around the Lake Houston area as well as from the inflow from the Spring Creek and West Fork of the San Jacinto River. This study will utilize learning materials from class and research papers to attempt a preliminary analysis of the impact of Hurricane Harvey.

INTRODUCTION AND BACKGROUND

Hurricane Harvey, one of the most damaging natural disasters in the U.S., dropped around 27 trillion gallons of water on Texas and Louisiana.[1,2] Since 1980, 218 billion dollar climate events have incurred total damages exceeding $1.2 trillion, without incorporating the damages by Harvey, Irma and Maria, which are currently being assessed.[3] Some estimates put the costs for Hurricane Harvey between $90 – 120 billion.

NHC, Google Earth



NHC, ArcGIS Pro

Figure 1. National Hurricane Center's best track data for Hurricane Harvey in (a) Google Earth and (b) ArcGIS Pro

Many factors contributed to the extent of the flooding due to the storm event. Firstly, the jet stream failed to redirect the storm path due to its position in more northern latitudes in August.[4,5] Secondly, the storm absorbed a large amount of water from the warm oceans, which was released after making landfall, while passing over many rivers and bayous and impervious urban surfaces.[5] The vulnerability of the region to severe flooding and damages further exacerbated by the socio-economic conditions[6], zoning laws and transportation infrastructure.

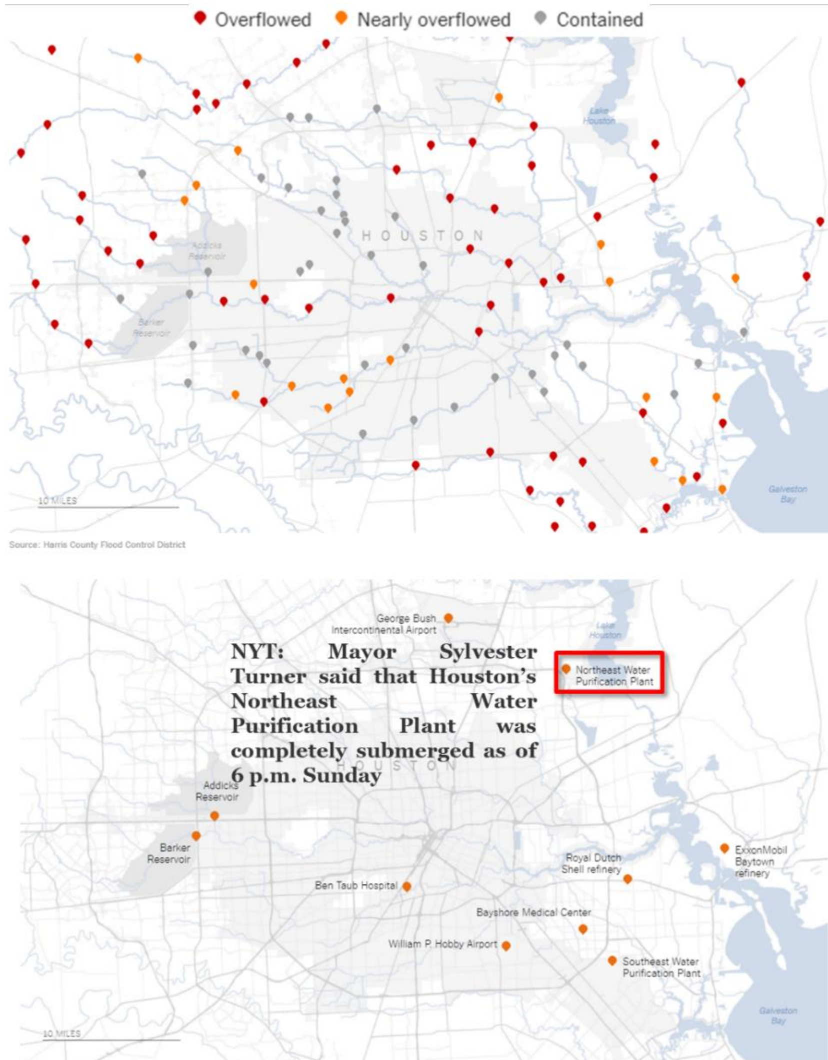


Figure 2. Notable issues in the city of Houston due to the hurricane and related flooding

The flood waters left over by Hurricane Harvey were reported to contain high quantities of fecal matter and coliform counts. New York Times reported that the neighborhood of Briarhills Parkway was exposed to floodwaters with more than four times the *Escherichia coli* (*E. coli*) than considered safe.[7] Some sources of these contaminants could be breached water treatment facilities, agricultural/ranch areas upstream of rivers. While the hurricane has directly or indirectly taken the lives of at least 88 Texans, Department of State Health Services, the state health agency found 26 deaths caused by medical conditions, electrocution, traffic accidents, flood water-related infections, fires and burns.[8]

The current study aims to visualize the impact of Hurricane Harvey in the Lake Houston area. Precipitation, effects on water quality and level of inundation is assessed by utilizing the geoprocessing capabilities of ArcGIS Pro and data sourced from various government agency databases.

DATA SOURCES

DATASET	SOURCE	DESCRIPTION
Gage Height	USGS - NWIS	The U.S. Geological Survey's (USGS) National Water Information System (NWIS) supplies geographically seamless water data for the nation. With water data collected at over 1.5 million sites around the country, time-series data is provided that help to describe stream levels, streamflow (discharge), reservoir and lake levels, surface-water quality, and rainfall.
Hurricane Track	NOAA - NHC	NHC GIS Archive provides historical storm track data for tropical storms which can be downloaded in the form of shapefiles that contain the location of the center of the storm, path of storm, and wind swath, respectively.
Watershed Boundary	USGS	The Watershed Boundary Dataset (WBD) defines the extent of surface water drainage area to a point, accounting for all land and surface areas. By defining Hydrologic Units (HU) for the Watershed Boundary Dataset, it is possible to establish a base-line drainage boundary framework. Hydrologic units are given a Hydrologic Unit Code (HUC), which describes where the unit is in the country and the level of the unit.
County Line	US Census Bureau	The cartographic boundary shapefiles from the US Census Bureau are simplified representations of selected geographic areas from the MAF/TIGER geographic database.
Hydrography Data	EPA/USGS	National Hydrography Dataset Plus (NHDPlusV2) is a national geospatial surface water framework. The U.S. EPA developed and maintains NHDPlus in partnership with the U.S. Geological Survey. With incorporated features from the WBD, NHD and NED, NHDPlusV2 is useful in estimating stream flow volume, velocity and value added attributes like stream order and associated catchments.
Landcover (NLCD 2011) And Impervious Surfaces (NLCD 2011)	Multi-Resolution Land Characteristics (MRLC) Consortium	With a 16-class land cover classification scheme at a spatial resolution of 30 m, NLCD 2011 describes the land cover condition and the change occurring between 2006 and 2011. Data for the NLCD 2011 products are derived from the Landsat 5 Thematic Mapper (TM) imagery, providing spectral change analysis, land cover classification, and imperviousness modeling.
Elevation	USGS	The National Elevation Dataset (NED) is a seamless raster product, providing elevation data coverage of the continental United States, Alaska, Hawaii, and the island territories. The horizontal datum for NED is the North American Datum of 1983 (NAD 83), and the vertical datum is the North American Vertical Datum of 1988 (NAVD 88).
Daily Precipitation (GHCN-Daily)	NWS-NOAA	The Global Historical Climatological Network (GHCN) database provides daily climate summaries from land surface stations across the globe. Currently, the GHCN-Daily contains the most complete collection of U.S. daily climate summaries.
High Water Mark	USGS	Manually recorded high water mark data by USGS hydrologists uploaded to the flood event viewer application on the USGS webpage provides information that can be used to estimate how much land alongside a stream will be inundated at various stream levels.

OBJECTIVES

1. Delineate a basin with interesting characteristics to study and describe its features
2. Map the rainfall occurred during the hurricane event
3. Assess water quality changes in the area
4. Attempt to map the flood inundation in the basin using Height Above Nearest Drainage (HAND)

METHODOLOGY, RESULTS AND DISCUSSION

AREA OF INTEREST: SELECTION CRITERIA

The impact of Hurricane Harvey was spread over a vast area. The first objective was to locate a region with interesting characteristics to study. Lake Houston region appeared to be an interesting region for this study for several reasons.

Firstly, the stage height reported by USGS for the period during the hurricane was very high for a stream gage downstream of the lake, Stream Gage Site 08072050 San Jacinto Rv near Sheldon TX. Figure 3 from a New York Times report showed the high flow in the San Jacinto River which lies upstream of Lake Houston. Figure 4 shows the USGS gages around the Lake Houston region, with the associated gage height over time data for Site 08072050. The peak gage height attained on August 30th was more than 15 ft over the NWS Flood Stage level and crossed operational limit for the gage site as well. Secondly, the watershed area for Lake Houston has varied land use patterns, with agricultural and developed areas providing an interesting case study. Lastly, the presence of two lakes in this watershed may possibly help to balance out the effects of the flood by providing an equalization basin, mitigating effects of bad water quality or high flows.

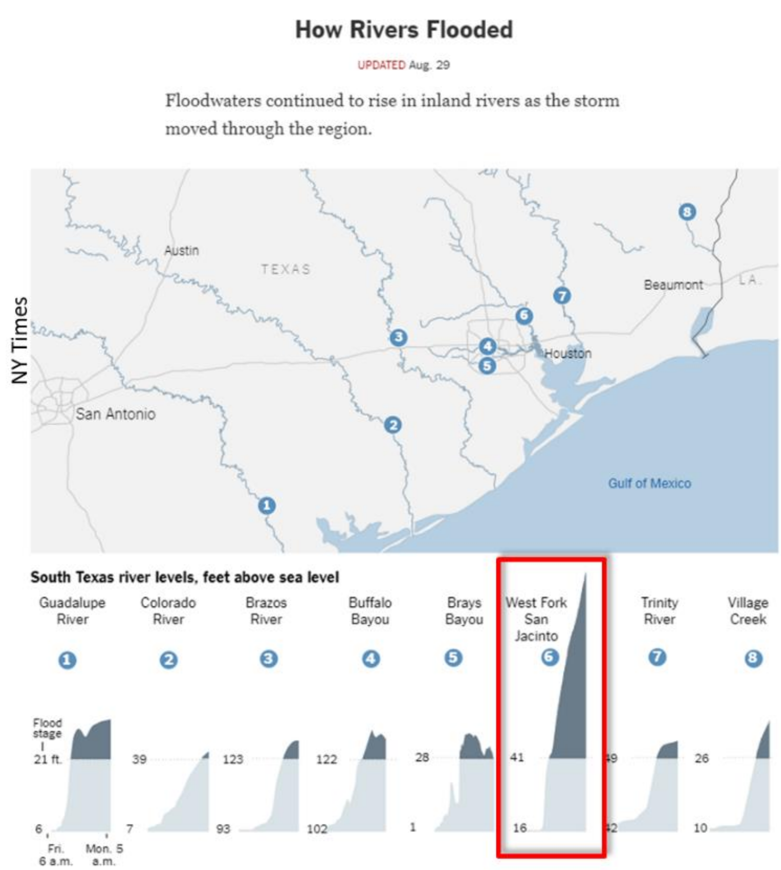


Figure 3. River levels along the path of Hurricane Harvey and their Flood Stages

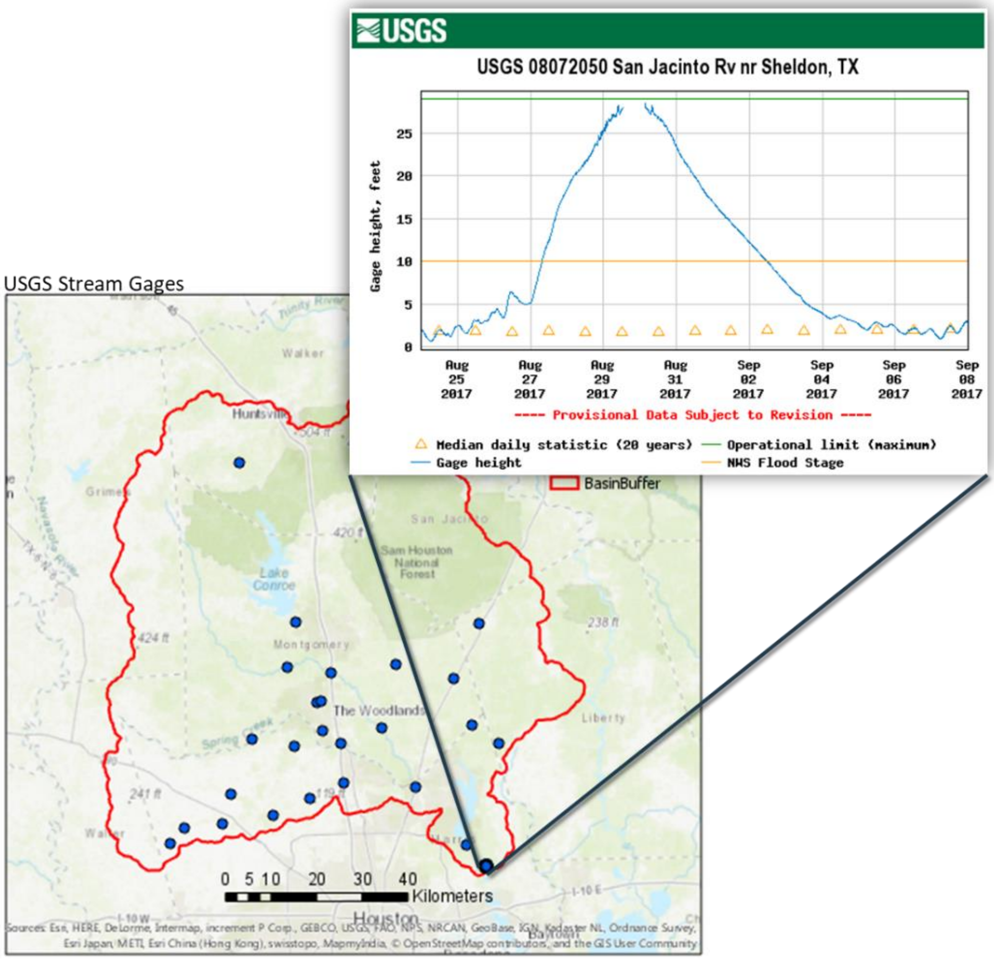


Figure 4. Watershed for the USGS gage located downstream of Lake Houston and the associated gage height data during the hurricane event. Blue dots represent the USGS Stream Gage sites within the basin.

With this in mind, the first step was to identify the watershed draining to this stream gage reporting a high flow. Using ArcGIS Pro and the class exercises, a watershed was delineated and the DEM for this region was extracted by utilizing the 30 m NED. The NHDPlusV2 flowlines within the basin were also extracted using ArcGIS Pro. A composite figure with the elevation, streamflow, USGS Gage site and basin buffer are presented in Figure 5. Other basin characteristics derived from ArcGIS Pro maps are presented below in Table 1.

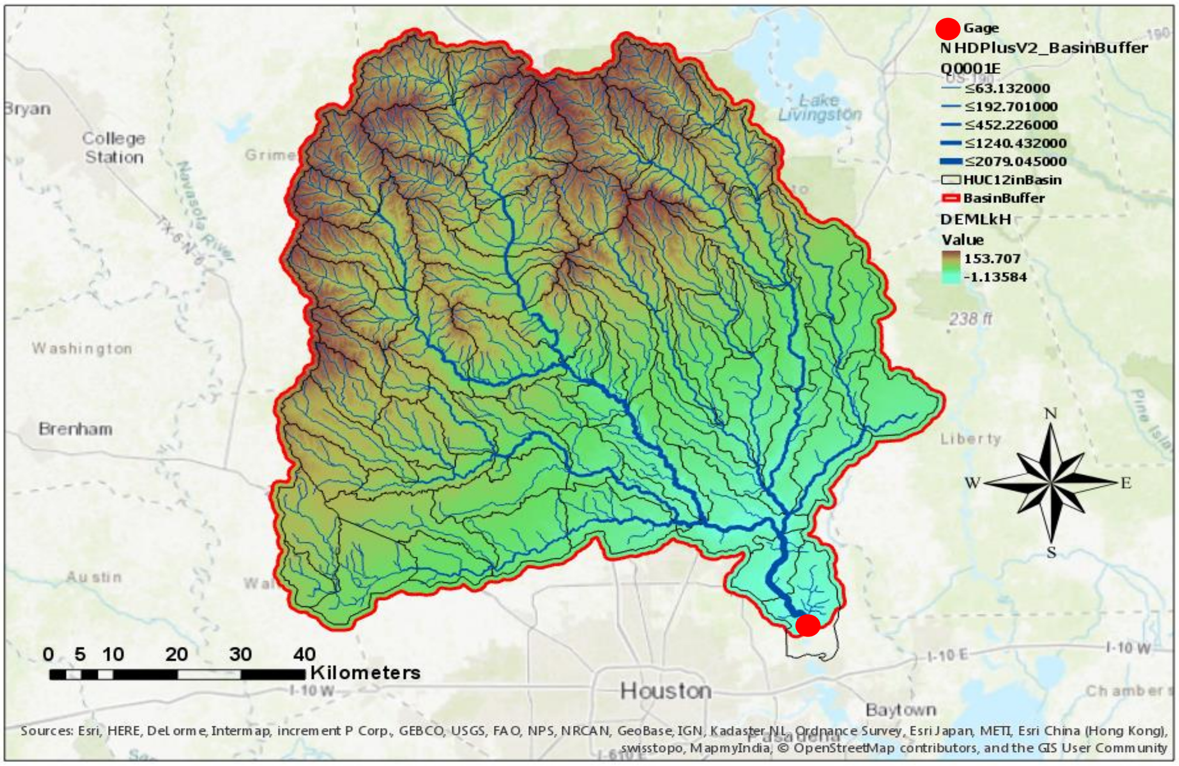


Figure 5. Watershed delineation, NHDPlusV2 flowlines and the Digital Elevation Model extracted for the basin.

While the north-western regions of the basin have higher elevations, the downstream region is flat, which can also be clearly visualized from Figure 6 (a) and (b) where the hillshade and contour maps of the region are presented.

Table 1. Basin characteristics and other information.

PARAMETER	VALUE
Basin Area (km^2)	7911.52
Counties within basin	7
HUC 10 Watersheds	12

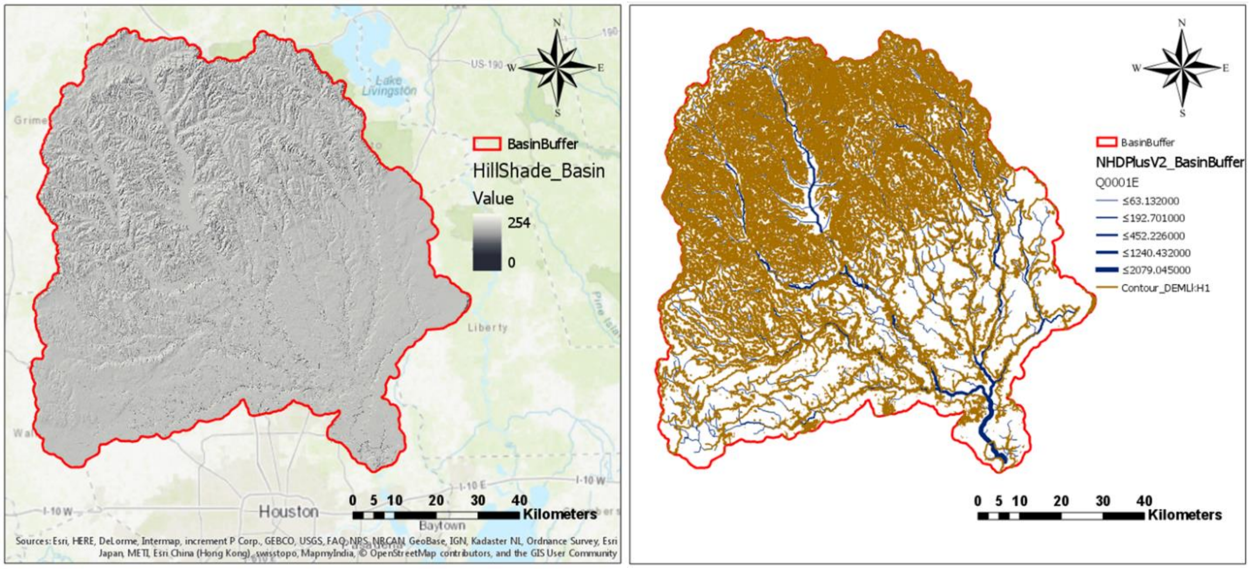


Figure 6. Hillshade and Contour maps for the basin area extracted from ArcGIS Pro. South-eastern parts of the basin are flat lands and may be prone to flooding events.

To obtain a more detailed understanding of how a flooding event can impact the water quality, the land use patterns within the basin was studied, to obtain the percentage of land use per category. The NLCD was obtained for Texas Gulf Region 12 and extracted by mask to the basin area. This was further reclassified to clean up the figure and provide a broad look into the main land use categories. Figure 7 displays the land use pattern within the basin. Table 2 reports the percentage of each land use category within the basin, calculated by multiplying the associated cell counts to the area of each cell. The regions represented in yellow represent agricultural land and pastures, accounting for almost 26% of the land use in the basin area. These are generally located at the upstream regions of the watershed, with higher elevations. During a high precipitation event, it would thus be likely that runoff from these agricultural regions would flow into the streams. Additionally, the downstream end of the basin lies north of the city of Houston, where developed regions – with more impervious surfaces - are likely to be found (Figure 8). If contaminants are transported from upstream regions and accumulate in the low-lying downstream end, it may pose a serious health hazard.

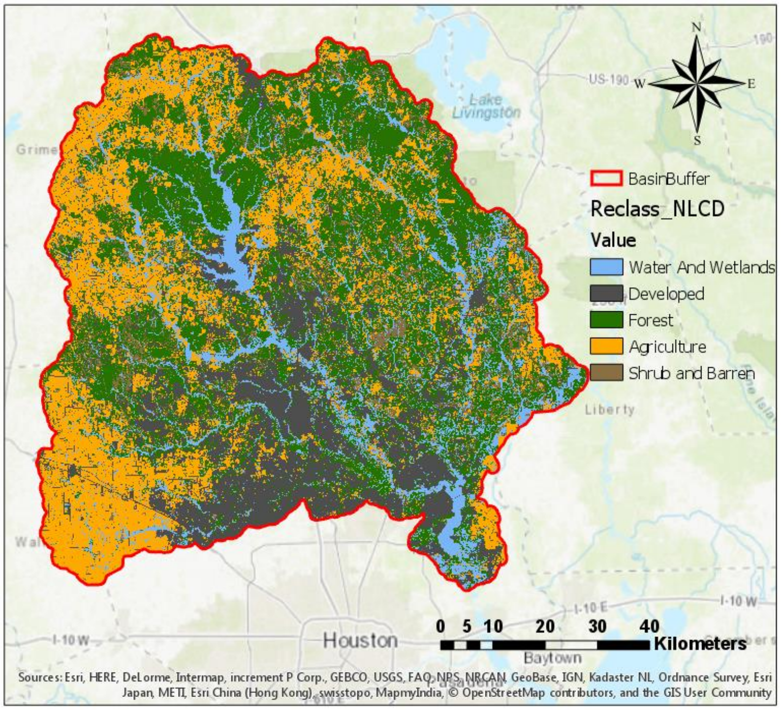


Figure 7. Land cover data for the basin, obtained from the NLCD dataset and reclassified in ArcGIS Pro.

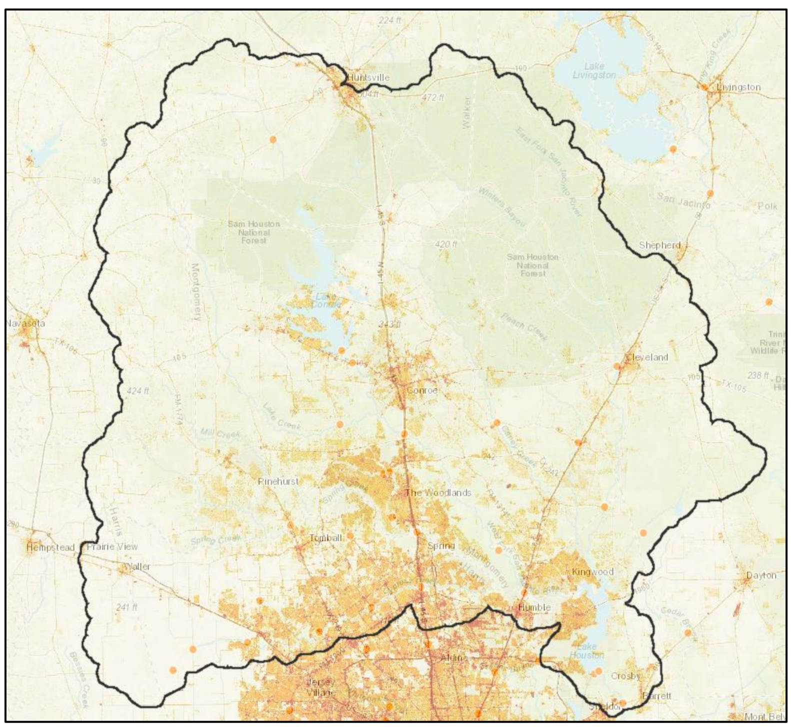


Figure 8. Impervious surfaces around the basin, obtain from a Living Atlas Layer in ArcGIS Online. These impervious surfaces closely align with the developed regions in Figure 7.

Table 2. Land use categories, calculated as percent of total basin area.

LAND COVER TYPE	AREA (SQ. KM)	% AREA
Water and Wetlands	1011.151	12.781
Developed	1548.009	19.567
Forest	**2688.685**	**33.986**
Agriculture	**2038.227**	**25.764**
Shrub and Barren	625.152	7.902
TOTAL AREA	7911.224	

MAPPING RAINFALL IN THE LAKE HOUSTON BASIN WITH SPLINE AND THIESSEN INTERPOLATIONS

Precipitation during Hurricane Harvey reached record levels. 24-hour Precipitation Summary data from August 24 to September 1 was obtained from the Global Historical Climatological Network (GHCN) database for the 7 counties which are within or along the basin boundary. The dates were chosen so as to account for sites that may have at least logged 3-5 days of data The 7-county precipitation data table was imported to ArcGIS Pro and processed so as to obtain a key field for each record. The data was further processed by summarizing the table by station ID and then obtaining a cumulative precipitation value in inches. A map was created to visualize the precipitation gages and their respective cumulative precipitation amounts using graduated symbols, presented in Figure 9.

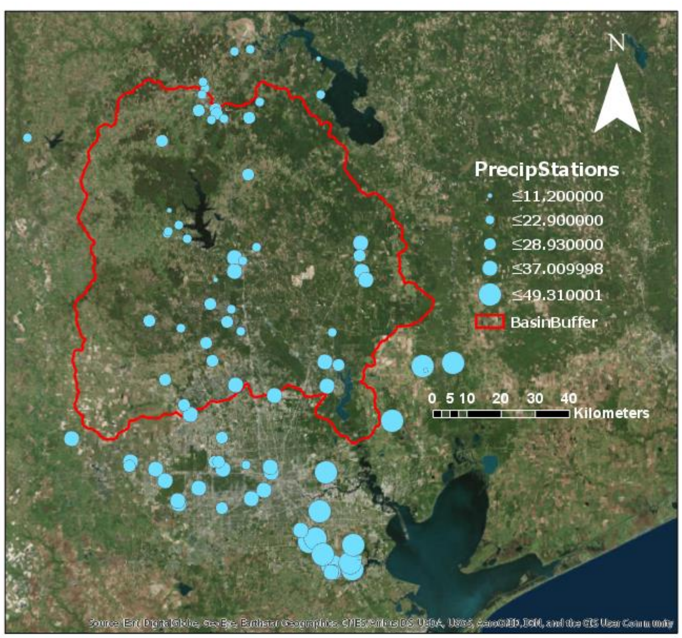


Figure 9. Precipitation stations within and around the basin area, with graduated symbols representing cumulative rainfall totals during the hurricane event.

Upon obtaining a simplified table with up to 9-day precipitation data for different precipitation stations in and around the basin, two methods were used to visualize and quantify the precipitation data.

Simplistic interpolation using the Thiessen Polygon method was used to obtain a spatially averaged precipitation value for each HUC 10 watershed in the basin using the precipitation station data. Figure 10 (a) depicts HUC10 watersheds and the Thiessen Polygons for the associated precipitation stations. The data was clipped to the basin. Area weighted precipitation based on Thiessen polygons was calculated as per instructions in the class exercises, using the following equation:

$$P_i = \frac{\sum_k A_{ik} * P_k}{\sum_k A_{ik}}$$

The summary table for HUC 10 watersheds are provided in Table 3. The highest amount of rainfall fell in the Buffalo Bayou-San Jacinto River watershed, with a total of 40.23 inches over 9 days. Buffalo Bayou, downstream of Lake Houston was thus prone to flooding from high precipitation amounts as well as high flows coming in from regions further upstream as well.

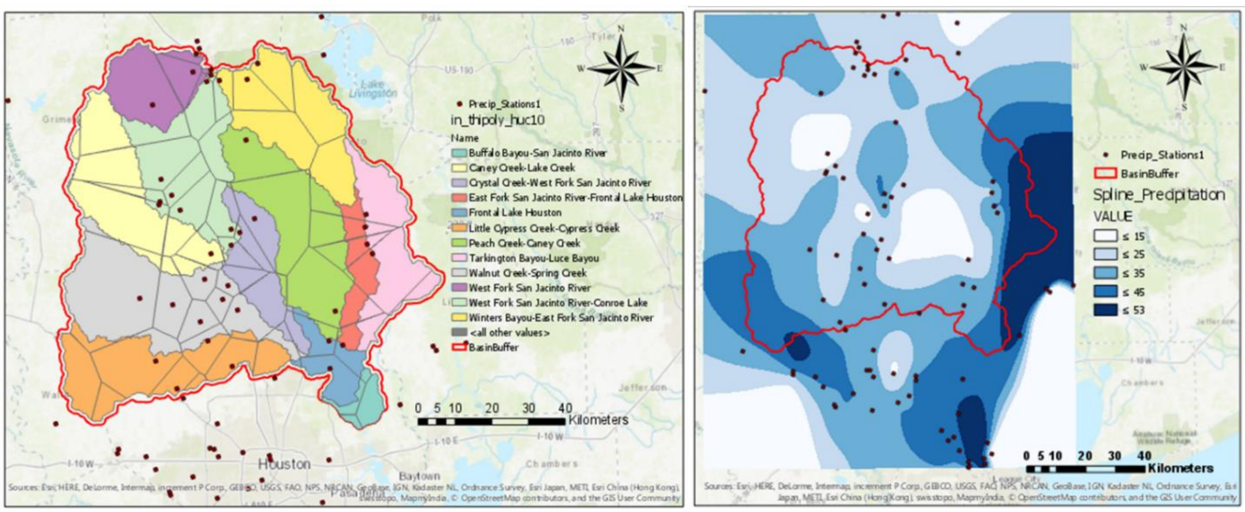


Figure 10. Precipitation data interpolation and visualization methods (a) Thiessen Polygon method and (b) Spline Interpolation method.

Spline interpolation was also utilized to create a visual representation of regions that received high precipitation during the storm event. Due to sparse precipitation data at the north west and north east corners of the basin and few stations reporting only 3 days of data, some regions represented lower rainfall as compared to maps presented by news and other media outlets. However, the south western region does show high rainfall amounts (also captured in the Buffalo Bayou HUC 10 rainfall totals) possibly due to the returning path of Hurricane Harvey causing sustained precipitation in the region.

Table 3. Summary table of results for the Thiessen polygon interpolation for a spatially averaged precipitation amount for HUC 10 watersheds within the basin.

HUC 10 NAME	10-DAY AREA WEIGHTED PRECIPITATION (IN)
West Fork San Jacinto River	25.30
West Fork San Jacinto River-Conroe Lake	19.33
Caney Creek-Lake Creek	18.58
Crystal Creek-West Fork San Jacinto River	22.83
Frontal Lake Houston	30.55
Little Cypress Creek-Cypress Creek	28.42
Walnut Creek-Spring Creek	24.84
Peach Creek-Caney Creek	22.06
Tarkington Bayou-Luce Bayou	31.96
Winters Bayou-East Fork San Jacinto River	24.37
East Fork San Jacinto River-Frontal Lake Houston	27.23
Buffalo Bayou-San Jacinto River	**40.23**

WATER QUALITY MAPPING

During the flooding from Hurricane Harvey, concerns regarding water quality in the streams and inundated locations were raised. Water quality data for the basin area, however, is not readily available for many of the USGS Stream Sites. A select few parameters, for which data is available from USGS-NWIS and USGS-Texas Real-Time Water Quality Information, were selected to obtain an overview of the changes that occurred during and days following the storm event.

Total phosphorous (TP) refers to the total amount of phosphorous compounds (e.g., phosphorous, orthophosphate) that are present in natural waters. This is an essential and limiting nutrient that can be readily utilized by the aquatic biota. This nutrient may be transported by discharge of waste water or via agricultural runoff. Since both of these sources could have possibly increased runoff during the storm event, this study hypothesized an increase in the TP amounts during and after the event. Figure 11 depicts the changes in computed TP for the third quarter of 2017 (Jul-Sep) for a stream gage located to the north east of Lake Houston. An interesting insight is that TP quantities have consistently remained above the water quality criteria mark, even before the storm event. A discrete, manually measured TP value during the storm returned a lower TP concentration. This may be explained by the dilution by the higher streamflow value (displayed in blue in Figure 11). However, overall, the storm did not seem to bring a significant increase in the TP trends. This hypothesis may need to be revised to account for dilution or other factors.

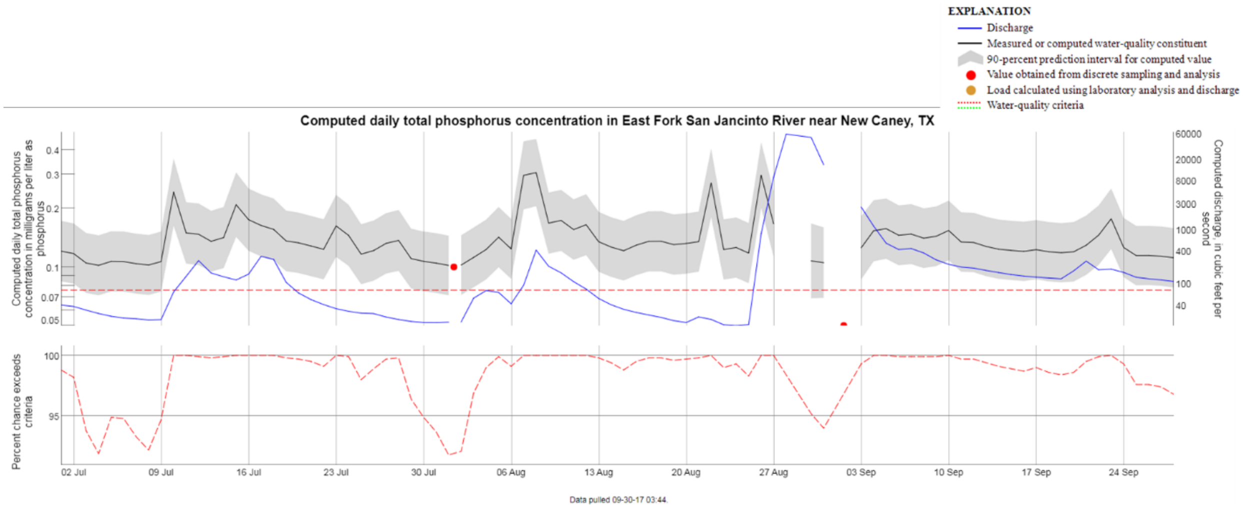


Figure 11. Total phosphorous concentration at the upstream (of Lake Houston) site: East Fork San Jacinto River near New Caney TX for the Jul-Sep quarter of 2017.

Total Nitrite and Nitrate, other essential nutrients for aquatic biota did not show any changes during the hurricane event.

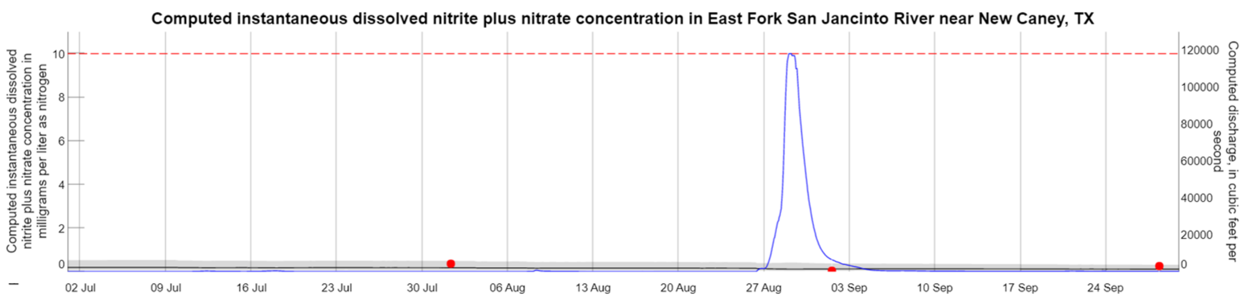


Figure 12. Total nitrite and nitrate concentration at the upstream (of Lake Houston) site: East Fork San Jacinto River Near New Caney TX for the Jul-Sep quarter of 2017.

Total Organic Carbon (TOC) may be contributed by decaying natural organic matter (NOM) as well as other sources, which can be used as an indicator of water quality. Figure 13 shows the changes in total organic carbon concentration at the same upstream stream gage as discussed for TP and Total Nitrate and Nitrite. There is an increase in the TOC concentrations around August 24, corresponding to the hurricane event.

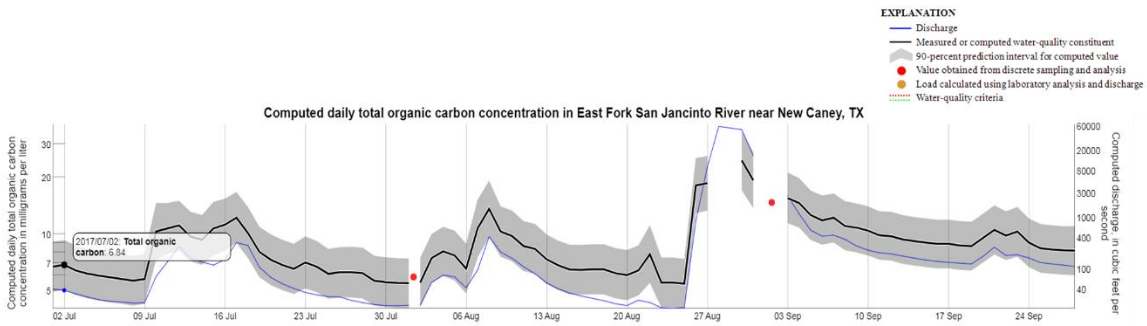


Figure 13. Computed daily total organic carbon concentration at the upstream (of Lake Houston) site: East Fork San Jacinto River Near New Caney TX for the Jul-Sep quarter of 2017.

Other parameters that were studied were dissolved oxygen (DO) and turbidity, obtained from the USGS-Texas Real-Time Water Quality Information portal. DO is essential for aquatic life, with low DO values commonly found during eutrophication, indicating poor health of the water body.[9] Turbidity is an optical indicator of suspended particulate matter in water. Turbidity may be caused by silt, fine organic or inorganic matter matter, algae, silt or other microscopic organisms. During a storm event, particulate matter can be transported with runoff into rivers and streams, causing higher turbidity values. High stream velocities and discharge rates can also increase mixing and suspend sediments from the river bed. High turbidity values can adversely affect light penetration and water quality, and may cause lakes to fill in faster.[10] Suspended sediment may also facilitate transport for other pollutants, notably metals and bacteria, via adsorption on surface sites. Thus, turbidity values may serve as a good indicator of potential pollution in a water body. Figure 14 shows water quality indicators at sites upstream, at the lake and downstream of Lake Houston with associated DO and turbidity values over the period of the storm event. While there is no clear trend for DO, the turbidity rapidly increases due to the hurricane event. As expected, the upstream and lake site showed turbidity changes earlier (around August 27) and the downstream site show turbidity surge around August 31, indicating the transport of the sediment and runoff.

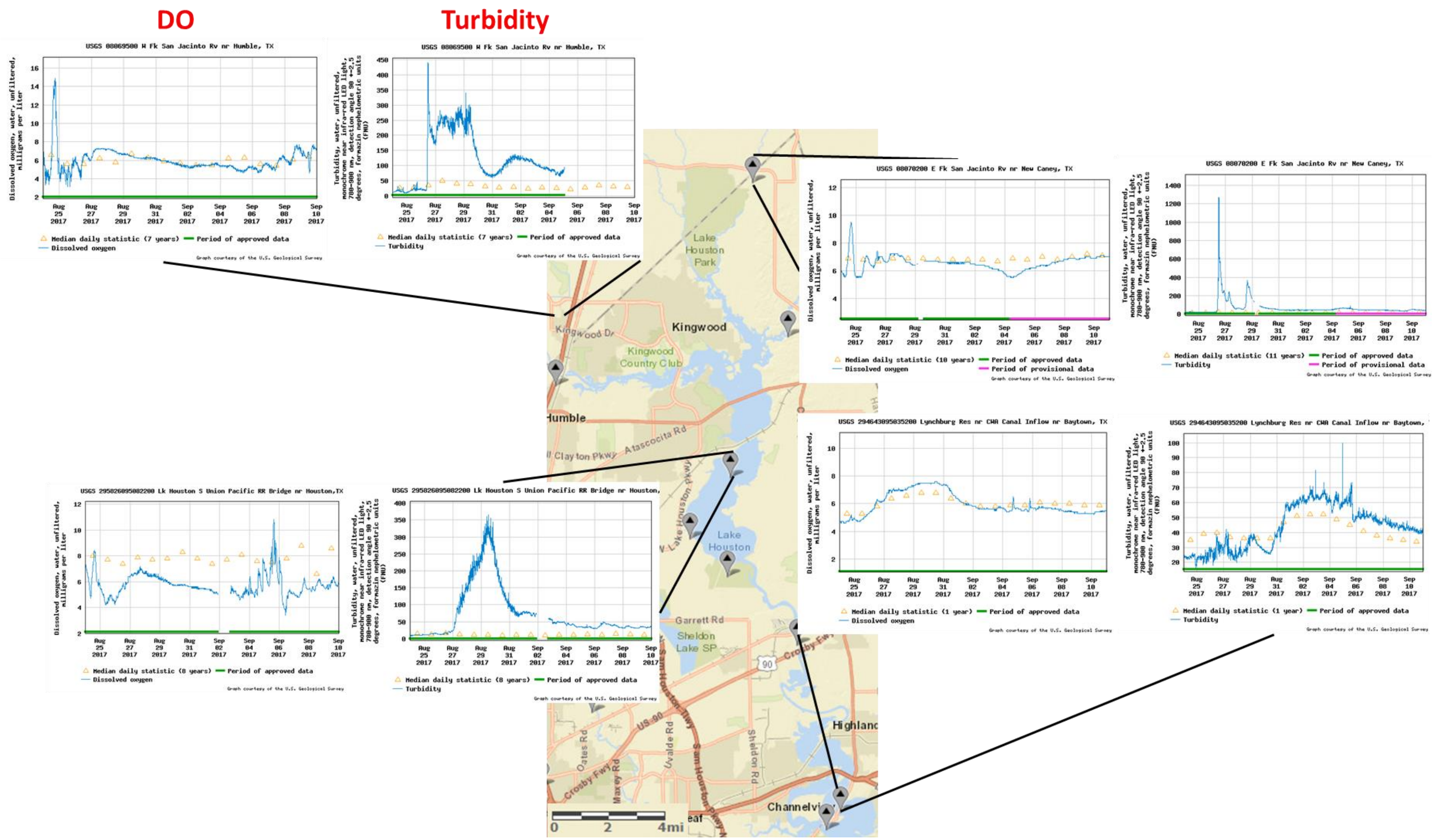


Figure 14. Water quality indicators for sites upstream and downstream of Lake Houston.

FLOOD ANALYSIS

Height above nearest drainage analysis was attempted by first obtaining 1/3 arc second NED data. These tiles were combined using Mosaic to New Raster and combined into one DEM tile. This tile was clipped to the Basin and saved as a tiff file. Procedure from Exercise 5 was utilized to obtain the height above nearest drainage for the basin. Processing in TauDEM took above 1.5 hours, likely due to the file size. TauDEM only returned 3 files and did not return the ad8o file after multiple attempts. Instead, to complete the flood analysis dataset, high water mark (HWM) data was obtained from USGS field data collection and mapped using ArcGIS Pro. First, the Very Poor and Poor Quality data was excluded using the Definition Query feature in the Properties tab. Next, any data that was logically inconsistent (e.g., 69 ft above ground) was also excluded. This dataset then provides a visual representation of where inundation due to flooding was severe. Figure 15 shows the USGS HWM data with graduated symbols for height above ground where the HWM was found. Some regions indicated 13 ft of inundation due to the storm event. Most of the HWMs were assessed at the south eastern regions of the basin. Buffalo Bayou and Kingwood areas around Lake Houston were heavily flooded during the storm, which is represented well by the HWM map showing heavy flooding in these residential and developed areas.

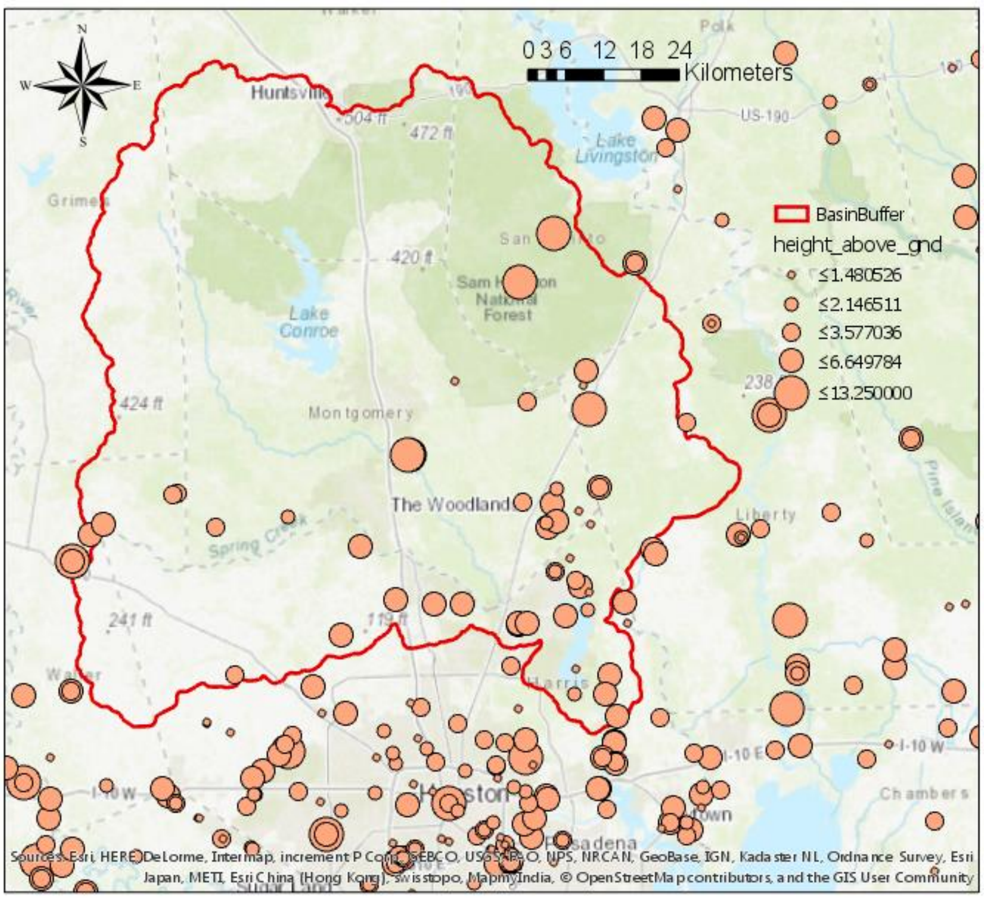


Figure 15. USGS HWM data represented as graduated symbols for the area under study.

SUMMARY AND CONCLUSIONS

This study was primarily an effort to visualize the impact of a storm event like Harvey using the ArcGIS Pro tools. First, the area of study was chosen based on high flow events and interesting surface features. Precipitation analysis agreed with reported data for south eastern regions of the basin, showing high precipitation totals for areas like the Buffalo Bayou-San Jacinto watershed. Spline interpolation and Thiessen polygon method provided a qualitative and quantitative measure of the precipitation totals. Thirdly, the water quality impacts for nutrient based contaminants did not seem to pose a higher than usual risk to the water bodies. Turbidity increased sharply during the storm and a transport pattern can be identified. However, this analysis was limited by available data as this was based on very few gages around Lake Houston. Lastly, the HWM mapping provided an insight into regions that were inundated in and around the basin. The study was able to successfully utilize geoprocessing capabilities of ArcGIS to map several aspects of a storm event, albeit at a preliminary scale.

LIMITATIONS

Availability of water quality data was a severe limitation for the term project. Height above nearest drainage could have provided a better picture about effects at the upstream regions and how the presence of lakes could modulate the effects of flooding by providing an equalization effect, however the analysis remained unsuccessful at the time of submission.

FURTHER STUDY IDEAS

Utilizing soil data, precipitation and some knowledge of hydrology, the study may be expanded to identify origins of runoff to be able to identify potentially important sources of pollution during a storm event. Time series mapping of pollutant transport can also be attempted to obtain insights on longer term effects of a storm event.

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