

FLOODING SURROUNDING THE ADDICKS RESERVOIR DURING HURRICANE HARVEY

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INTRODUCTION

When the Addicks and Barker Reservoirs were initially constructed in the 1940s, they were located outside of the city of Houston in a region dominated by agricultural land use.¹ After two major floods devastated Houston in 1929 and 1935, the reservoirs were constructed to mitigate damage to downtown Houston in future floods. Both reservoirs were designed to collect storm water and release it into the upper portion of Buffalo Bayou.² Buffalo Bayou then travels through downtown Houston to the Houston Ship Channel.

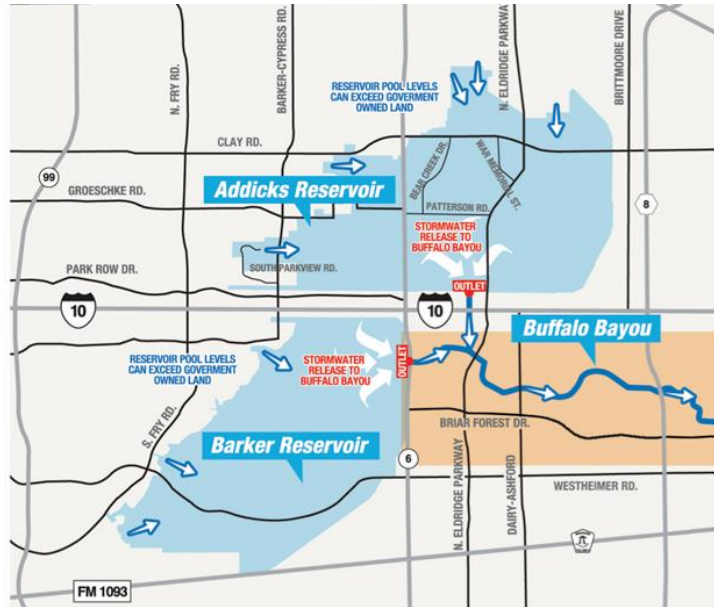


FIGURE 1: MAP OF ADDICKS AND BARKER RESERVOIR FLOWS²

As Houston developed, it enveloped the Addicks Reservoir. The US Army Corps of Engineers released a report following a record setting flood in March of 1992 warning that residents were unaware of the increased risk of flooding in developments near the reservoirs.³ The Corps proposed multiple options to reduce the risk, but none were pursued at the time.⁴ While the National Land Cover Datasets from 1992 and 2011 should not be directly compared to calculate changes in land cover, the increase in development upstream of the Addicks Reservoir is evident in figures 2 and 3.

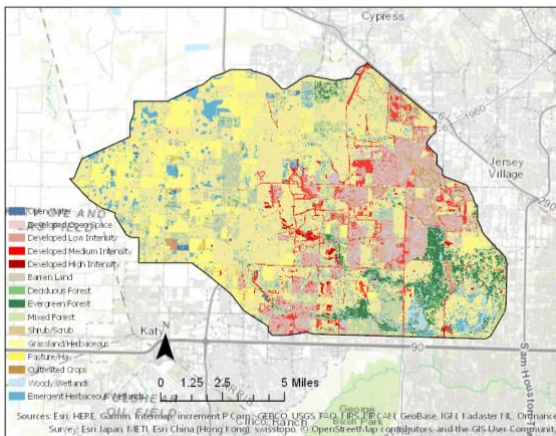


FIGURE 2: 1992 ADDICKS WATERSHED LAND COVER

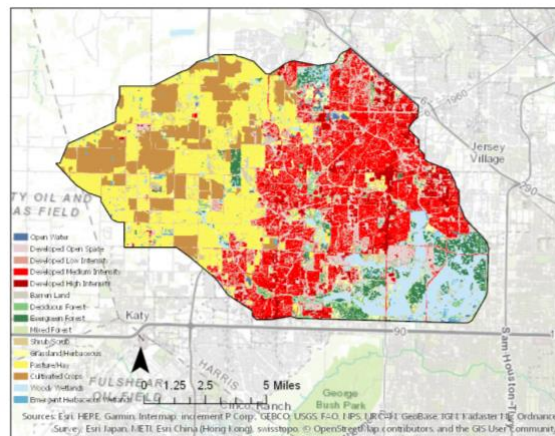


FIGURE 3: 2011 ADDICKS WATERSHED LAND COVER

At the time of Hurricane Harvey, approximately 31,000 homes were located in the reservoir flood pools upstream of the reservoirs in Harris and Fort Bend Counties.⁵ During the initial days of Hurricane Harvey in late August 2017, many of the neighborhoods located directly upstream of the Addicks Reservoir began to flood for the first time since the reservoir's construction. On August 28th, rising reservoir levels resulted in uncontrolled releases on the north end of the dam.⁶ To combat rising reservoir levels, the US Army Corps of Engineers began controlled releases into Buffalo Bayou from both the Addicks and Barker Reservoirs on August 29th. The controlled releases started at a flow rate of approximately 4,000 cfs from each reservoir and then were increased to approximately 8,000 cfs per reservoir.³ The City of Houston estimated that approximately 4,000 homes were affected by the increased flow through Buffalo Bayou.³ Even still, the Addicks Reservoir reached its peak height of 109.09 feet on August 30th.⁷ The Harris County Flood Control District estimated that 6,010 homes were flooded upstream of the Addicks Reservoir due to the filling of the reservoir.⁸

OBJECTIVES

This project examined flood inundation in the area surrounding the Addicks Reservoir during Hurricane Harvey. The first objective was to estimate the number of homes flooded upstream of the Addicks Reservoir when the reservoir filled using the Height Above Nearest Drainage (HAND) method. The estimate produced using the HAND method was then compared to estimates developed by the Harris County Flood Control District and the *Houston Chronicle*. The second objective was to estimate the number of homes flooded along Buffalo Bayou downstream of the Addicks and Barker Reservoirs due to the controlled releases. The estimate produced using the HAND method was then compared to estimates developed by the Harris County Flood Control District and the City of Houston.

METHODOLOGY AND DATA ANALYSIS

DATA DESCRIPTION

This analysis utilized the 10-meter Digital Elevation Model (DEM) from the USGS National Elevation Dataset. The National Hydrography Dataset Plus (NHDPlus) and the National Land Cover Database supplemented analysis performed with the DEM. Address points for the city of Houston were obtained from the Hurricane Harvey Collection on Hydroshare in order to estimate inundation. The historical data for stage heights was obtained from the Harris County Flood Warning System and Harris County Flood Control District. Maximum flowrates along Buffalo Bayou were found in the immediate flood report following Hurricane Harvey produced by the Harris County Flood Control District.

DATA ANALYSIS

UPSTREAM FLOODING

The accuracy of the DEM was crucial for the accuracy of the upstream inundation estimate as a whole. An elevation-area capacity curve of the Addicks Reservoir was developed in ArcGIS using both the original and filled DEMs to gain a better understanding of the accuracy. This process was automated by using the surface volume tool in conjunction with model builder.

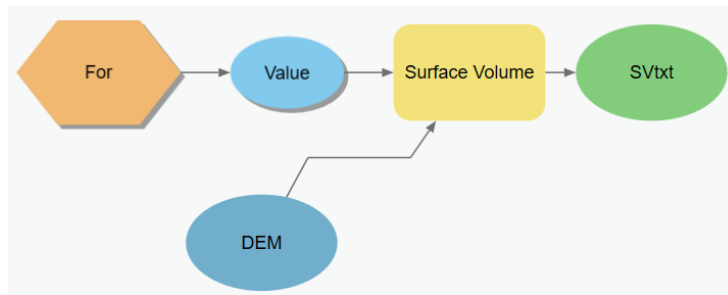


FIGURE 4: MODEL BUILDER USED TO DEVELOP ELEVATION-AREA CAPACITY CURVE

The ArcGIS-developed elevation-area capacity curves were then compared to the elevation-area capacity curve published by the US Army Corps of Engineers.⁹

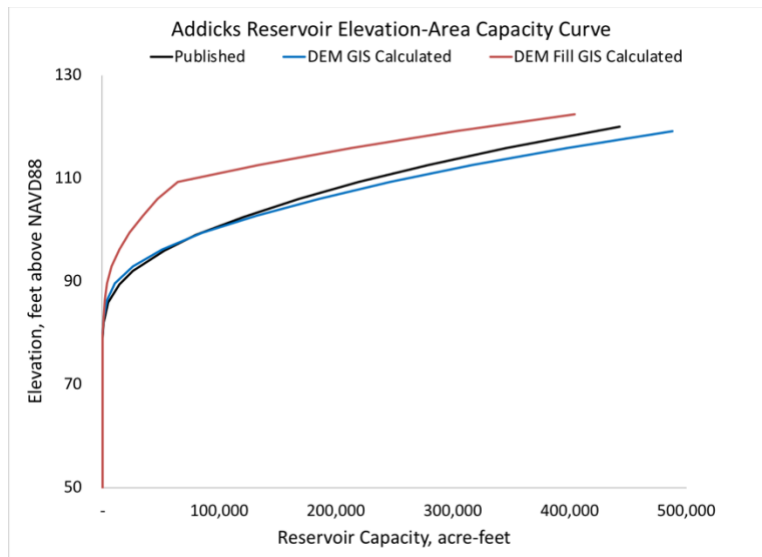


FIGURE 5: ARCGIS-GENERATED ELEVATION-AREA CAPACITY CURVE FOR ADDICKS RESERVOIR

While the original DEM provides a relatively accurate approximation of the reservoir capacity at lower elevations within the reservoir, it becomes less accurate over the full extent of the reservoir. The filled DEM deviates from the published elevation-area capacity curve at all reservoir elevations. Figure 6 shows the raster generated by subtracting the filled DEM from the

original DEM. Since the majority of the alterations were made to the area which encompasses the Addicks Reservoir, the deviation of the filled reservoir is intuitive.

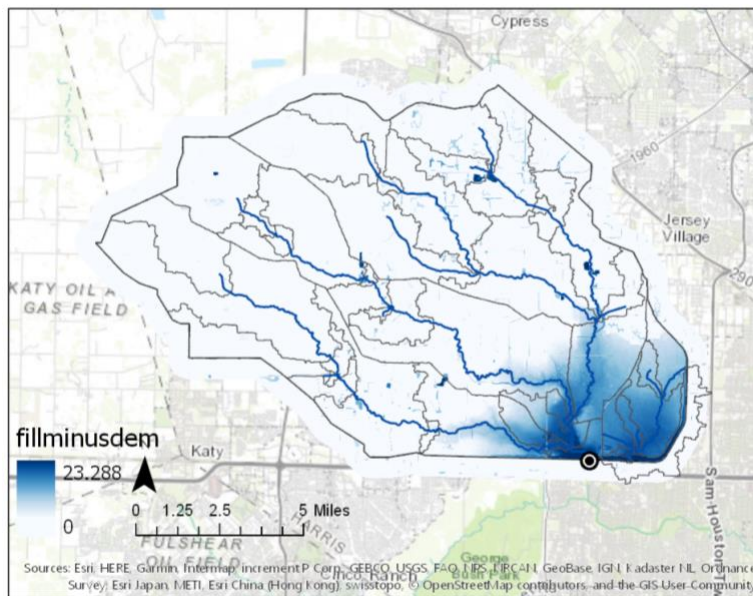


FIGURE 6: DIFFERENTIAL BETWEEN FILLED AND UNFILLED DEM OF ADDICKS WATERSHED

The filled DEM was used to calculate the flow direction using both the D8 and Dinfinitly methods. The flow accumulation was then calculated in reference to the outlet point of the reservoir seen in figure 6. The vertical flow distance was calculated using the Dinfinitly flow direction in relation to the outlet of the reservoir to produce the HAND values for the Addicks Watershed.

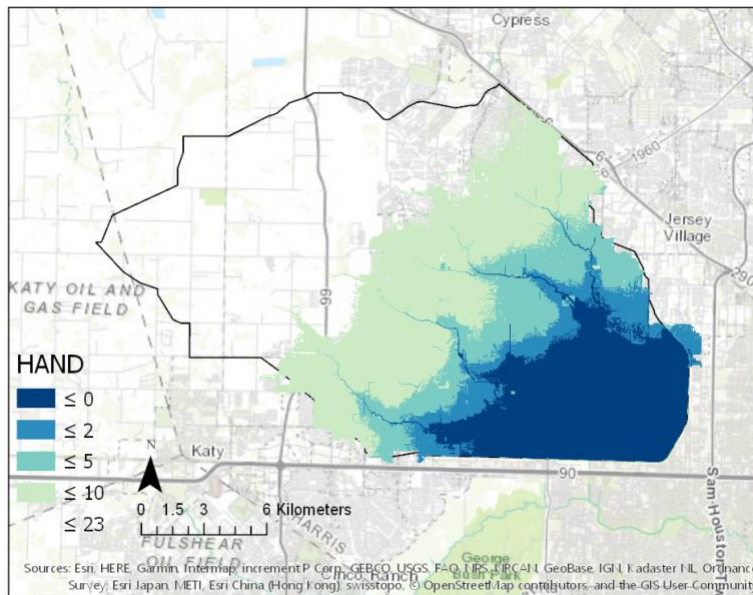


FIGURE 7: HAND ANALYSIS OF ADDICKS WATERSHED

The HAND values were applied to address points within the reservoir. The inundation depth in relation to the reservoir height was calculated using the reservoir heights reported by the Harris County Flood Control District during Hurricane Harvey.

DOWNSTREAM FLOODING

The analysis of flooding downstream of the reservoirs used a methodology similar to that used for upstream flooding. A watershed was delineated from downstream of the Addicks and Barker Reservoir to the convergence of Buffalo Bayou and White Oak Bayou on the western edge of downtown Houston. While Buffalo Bayou extends through downtown Houston, the analysis was limited in order to study the section of Buffalo Bayou that was most directly affected by the controlled releases from the reservoirs. A 10-meter DEM of the watershed was filled in ArcGIS. The filled DEM was used to calculate the flow direction using both the D8 and Dinfinitly methods. The flow accumulation was then calculated in reference to a stream network delineated from the original digital elevation model. The vertical flow distance was calculated using the Dinfinitly flow direction in relation to the stream network to produce the HAND values. The HAND values were applied to address points within the watershed.

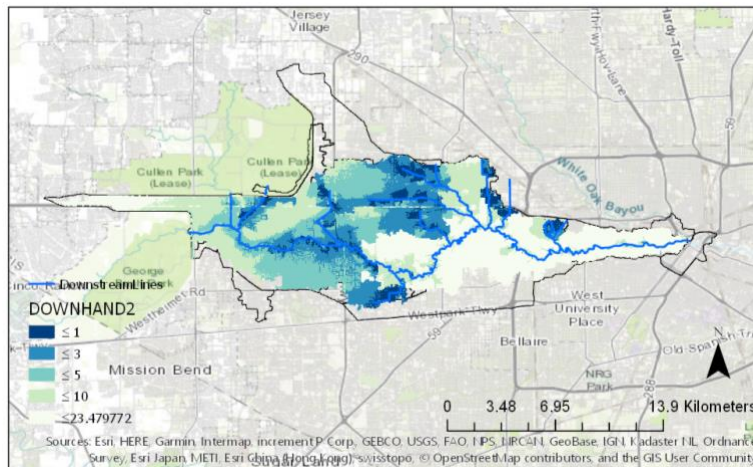


FIGURE 8: HAND ANALYSIS OF THE BUFFALO BAYOU WATERSHED

A Model Builder was developed to calculate the hydraulic properties in the delineated catchments along the main branch of Buffalo Bayou. The Model Builder required the user to select the catchment to be analyzed and required the input of the drainage lines, delineated catchments, and HAND raster.

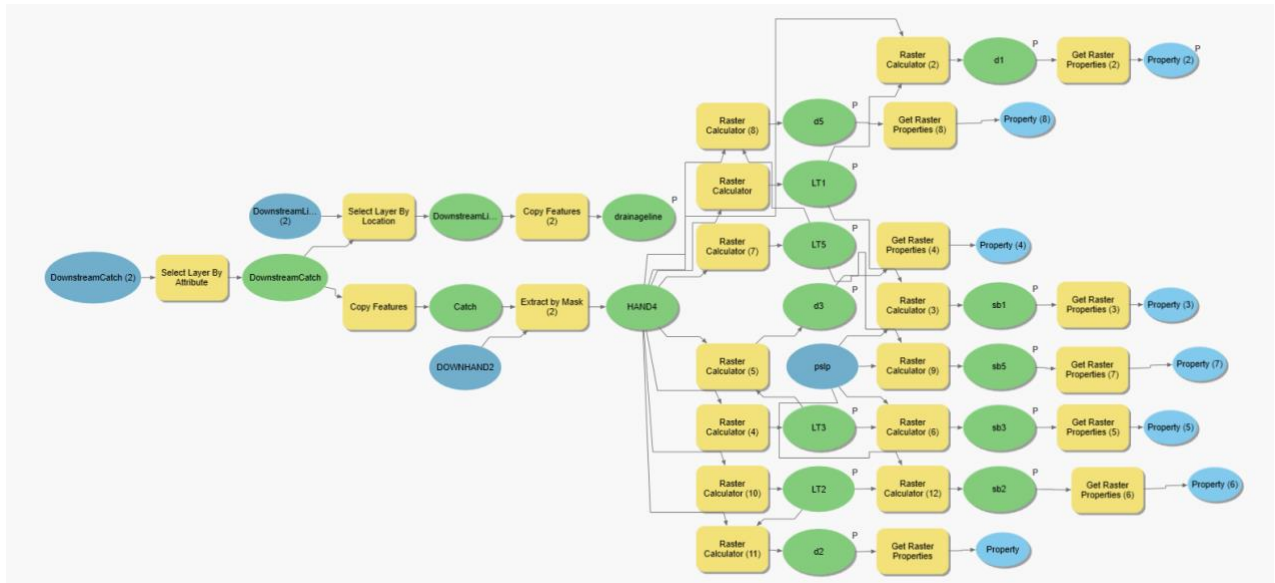


FIGURE 9: MODEL BUILDER TO DEVELOP HYDRAULIC CHARACTERISTICS OF CATCHMENTS

Hydraulic properties were calculated for stage heights of 1, 2, 3, and 5 meters. The Model Builder was initially intended to calculate the hydraulic properties in half-meter increments between stage heights of one and ten meters. However, due to the increased computing time and relatively small range of relevant flow rates, the functionality of the Model Builder was reduced. Instead, the initial stage heights were used to gain a better understanding of the range where the flow rate of interest would occur. The rating curves were then refined by adding stage heights at 0.25-meter increments near the flow rate of interest. One of the rating curves produced using this methodology can be seen in the figure below.

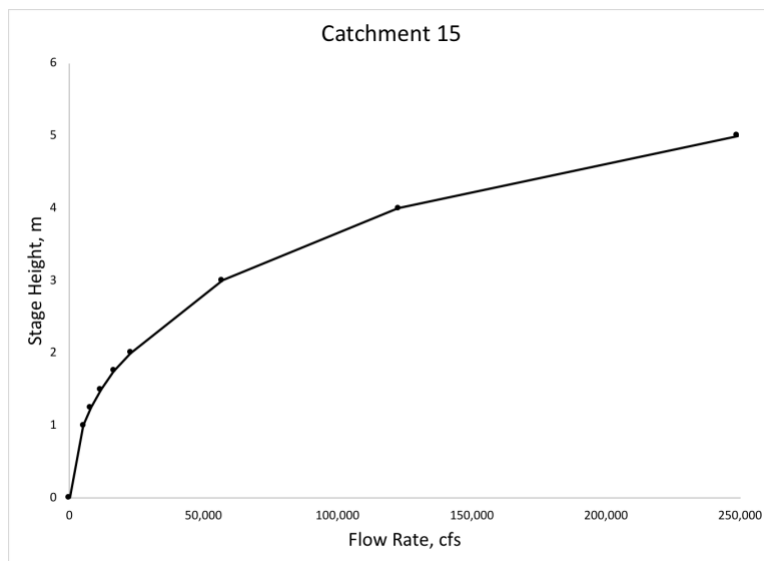


FIGURE 10: RATING CURVE FOR CATCHMENTS 15

Maximum flow rate data from the Harris County Flood Warning system was used in conjunction with the rating curves in order to interpolate maximum expected stage heights in each catchment during Hurricane Harvey. Another Model Builder extracted the address points in each catchment based on the interpolated stage height.

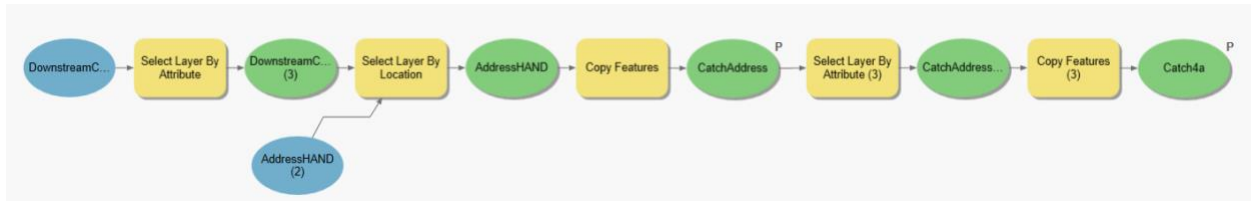


FIGURE 11: MODEL BUILDER TO EXTRACT ADDRESS POINTS

RESULTS

UPSTREAM FLOODING

The inundation map produced by the HAND analysis was similar to the inundation map produced by the US Army Corps of Engineers.¹⁰ However, the estimate of home inundation upstream of the Addicks Reservoir produced by the HAND method deviated substantially from the estimate produced by the Harris County Flood Control District. The HAND analysis estimated 3,329 homes were flooded upstream of the Addicks Reservoir when the reservoir filled. This estimate has a 45% error as compared to the Harris County Flood Control District’s estimate of 6,010 homes flooded in the Addicks Watershed.⁸

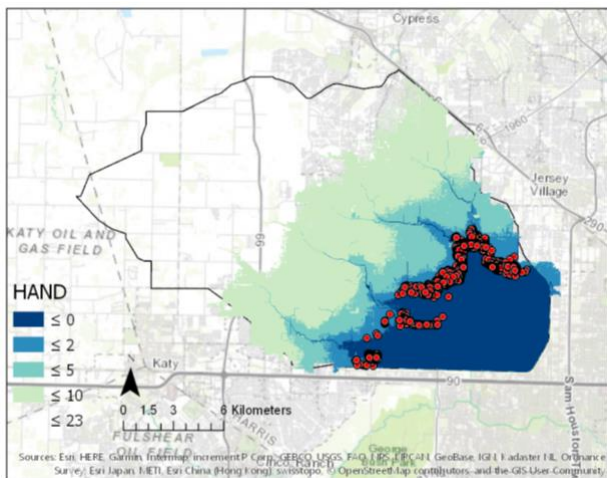


FIGURE 12: INUNDATION MAP PRODUCED BY HAND ANALYSIS

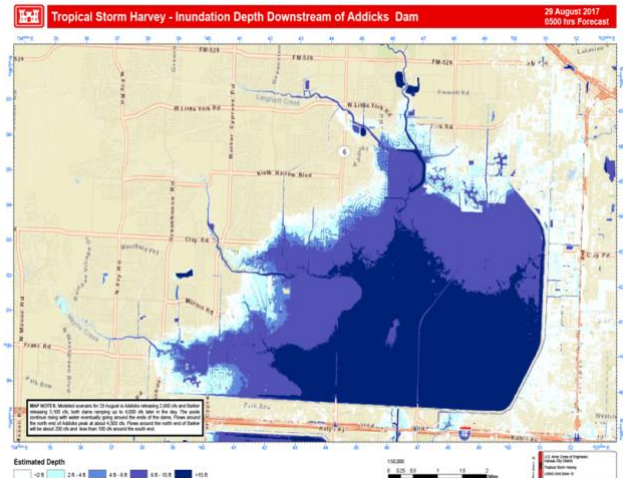


FIGURE 13: INUNDATION MAP PRODUCED BY THE CORPS¹⁰

In addition to the potential inaccuracy of the estimate, the estimate produced by the original HAND analysis cannot estimate home inundation below approximately 108 feet above NAVD88 due to the manner in which the DEM was filled. Since the reservoir did not reach a height of 108 feet above NAVD88 until August 29th, the analysis produced by the HAND method was unable to predict home flooding for the first few days of Hurricane Harvey.

TABLE 1: HOME INUNDATION CALCULATED BY ORIGINAL HAND ANALYSIS

	Height, ft above NAVD88	Homes Flooded
Filled DEM Reservoir Base (HAND = 0)	107.8	1,445
August 29th, 2017	108.85	2,896
Maximum Observed Height	109.1	3,329

In order to differentiate between homes assigned a HAND value of zero, the differential between the filled and unfilled DEM was used to adjust the originally calculated HAND values. A secondary reference plane was then defined below the original reference plane so that the original HAND values, adjusted HAND values, and reported reservoir heights could be easily related. This method could likely be refined to produce a more accurate method of estimating inundation in similar situations. The adjusted HAND values were applied to address points in the Addicks Watershed to allow for inundation estimation below a reservoir height of 108 feet above NAVD88. The table below shows the home inundation estimate for each day of Hurricane Harvey.

TABLE 2: HOME INUNDATION CALCULATED BY ADJUSTED HAND ANALYSIS

	Height, ft above NAVD88	Homes Flooded
August 25th, 2017	69	0
August 26th, 2017	90	0
August 27th, 2017	100	7
August 28th, 2017	106.9	966
August 29th, 2017	108.85	2,891
Maximum Observed Height	109.1	3,335
1% Error	110.2	5,566
2% Error	111.3	7,589

Since the secondary reference plane was defined in relation to the original plane, the second method produced approximately the same inundation estimate. As seen in the table above, relatively small changes in the height of the reservoir resulted in fairly substantial changes in

the inundation estimate. This is partially due to the high population density, as seen in the inundation map below. The instability of the inundation estimate can be better quantified through the graph below. This instability in conjunction with the potential inaccuracy of the DEM likely contributed to the large percent error. It is likely that the estimate would have been more accurate if LIDAR data had been used instead of the 10-meter DEM.

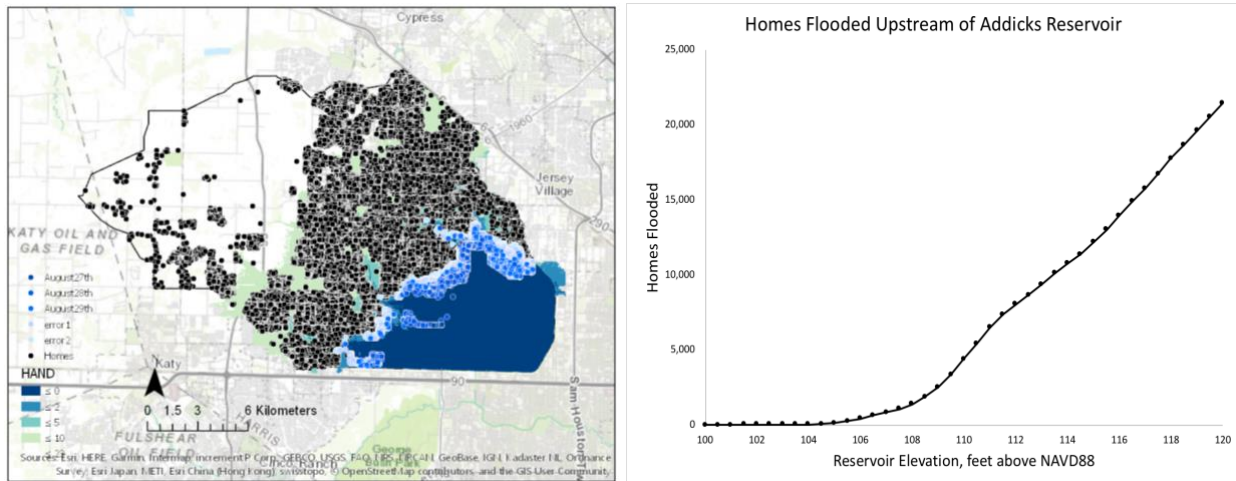


FIGURE 14: HOME INUNDATION IN THE ADDICKS WATERSHED

The extent of the study may have also contributed to the 45% error. The Harris County Flood Control District’s estimate is for the entirety of the Addicks Watershed. During Hurricane Harvey, high peak inflows on creeks and streams that drain to the Addicks Reservoir may have resulted in flooding along these waterways.⁸ The estimate produced using the HAND method did not include home inundation along waterways in the Addicks Watershed. Another study conducted by the *Houston Chronicle* estimated 5,000 to 6,000 homes were flooded in the area upstream of the Addicks Reservoir due to the filling of the reservoir.⁴ As such, flooding along waterways in the Addicks Watershed did not contribute substantially to the percent error.

DOWNSTREAM FLOODING

Maps of home inundation along Buffalo Bayou downstream of the Addicks and Barker Reservoirs can be seen in figures 15 and 16. The HAND analysis predicted that the majority of the flooding occurred directly downstream of the convergence of the outlets of the Barker and Addicks Reservoirs. This analysis appears to roughly approximate the inundation map produced by the US Army Corps of Engineers.

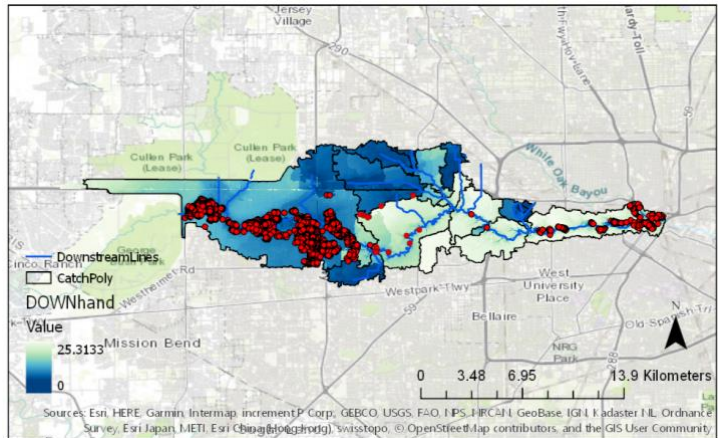


FIGURE 15: INUNDATION MAP PRODUCED BY HAND ANALYSIS

The HAND method estimated 3,929 homes flooded downstream of the Addicks and Barker Reservoirs due to the controlled releases. The City of Houston estimated that approximately 4,000 homes would be affected by the controlled releases. While the HAND method produced an inundation estimate similar to that of the City of Houston, there were catchments where the HAND analysis predicted home flooding deviated substantially from the inundation map produced by the US Army Corps of Engineers. LIDAR data would have likely improved the accuracy of the estimate in these catchments.

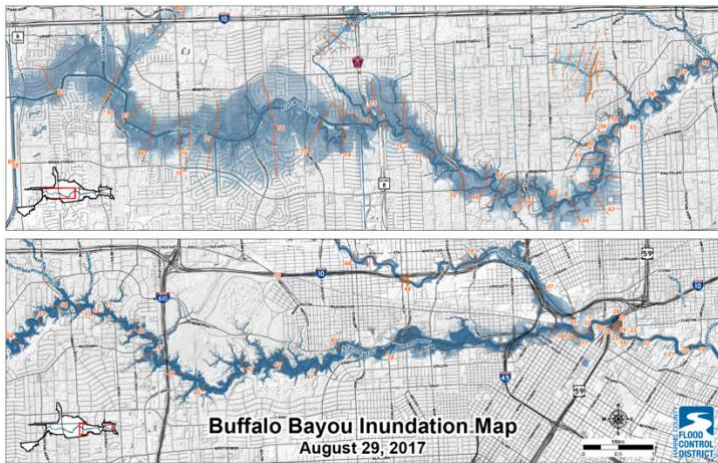


FIGURE 16: INUNDATION MAP PRODUCED BY THE CORPS¹⁰

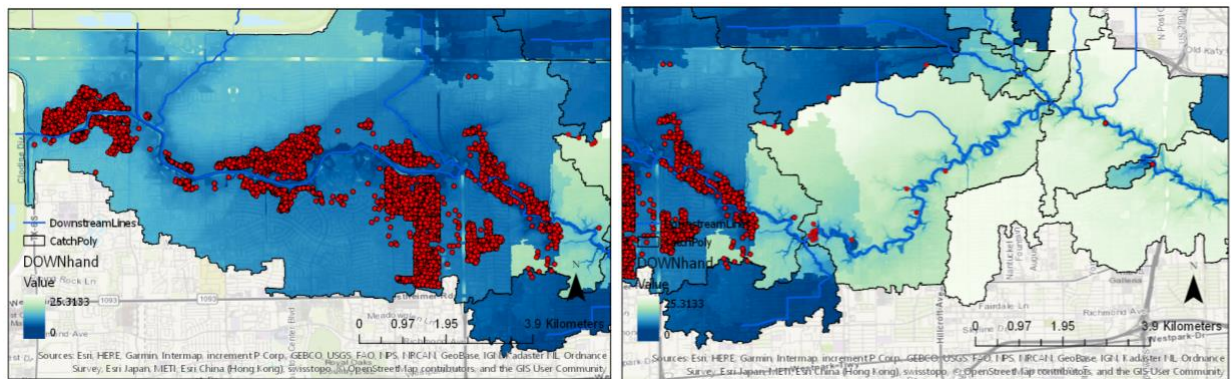


FIGURE 17: DISCREPANCIES IN INUNDATION ESTIMATES

The Harris County Flood Control District estimated that 17,090 homes flooded in the Buffalo Bayou watershed during Hurricane Harvey.⁸ This estimate deviates substantially from the estimate produced by the HAND method for a variety of reason. This study only examined the portion of Buffalo Bayou upstream of downtown Houston. In contrast, the Harris County Flood Control District estimate includes inundation in downtown Houston and east of downtown Houston. Additionally, the analysis produced by the HAND method only examined inundation along the main branch of Buffalo Bayou. These differences likely contributed to the large discrepancy between the estimate produced by the Harris County Flood Control District and the estimate produced by the HAND method.

CONCLUSION AND LIMITATIONS

This analysis used the HAND method to estimate home inundation both upstream and downstream of the Addicks Reservoir during Hurricane Harvey. The inundation estimate downstream of the Addicks and Barker Reservoirs produced an estimate comparable to the City of Houston's initial estimate. In contrast, the estimate of home inundation upstream of the Addicks Reservoir deviated substantially from the estimates developed by both the Harris County Flood Control District and the *Houston Chronicle*.

While there are a variety of factors that may have contributed to the inaccuracy of the estimates individually, one underlying issue in the analysis was the accuracy of the DEM. As seen in the upstream flooding analysis, the elevation-area capacity curve developed from the digital elevation model deviated over the extent of the reservoir. The accuracy of the DEM was highlighted again when just a 1% change in the reservoir height resulted in a 2,000-home change in the inundation estimate. In the downstream flooding analysis, discrepancies between the Harris County Flood Control District's inundation map and the HAND analysis were potential indicators of inaccuracies in the DEM. LIDAR data would have likely improved the accuracy of both the upstream and downstream estimates.

Both portions of this study highlighted the risk of increased development in the area surrounding the Addicks and Barker Reservoirs. Many homeowners in the highly developed regions upstream of the Addicks and Barker Reservoir were unaware of the potential hazards of living near the reservoirs.⁵ Similar issues were seen throughout the Houston during Hurricane Harvey when other dams and reservoirs were taxed. As Houston continues to expand and improve its flood infrastructure, it important to understand and improve the interactions between these highly developed regions and the existing and proposed flood infrastructure.

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