When is Drone Photogrammetry Useful for Flood Risk Assessment?

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1. Abstract

Drone technology and the high resolution datasets it enables stand to revolutionize our understanding of the Earth's surface. This research is Houston specific, and studies how drones can be used to systematically collect photogrammic data to detect environmental changes, and how that data is valuable for flood planning purposes.

This data is the culmination of three years of research. Prior to this year, the focus has been learning to fly the drone, learning the image processing Pix4D and ArcMap 10.5, and creating a workflow for accurate image collection processing. This study has collected three separate datasets of the study area at Buffalo Bayou using a DJI Phantom 4 Pro drone. This data was then processed and modeled in Pix4D to create digital elevation models (DEMs). The DEMs were calibrated and analyzed in GIS, and compared to the publicly available 2018 LIDAR data. Our research catalogs high resolution change over time of our study area, and documents the process of how drones can be used to systematically observe change over time. Additionally, our data highlights the difference in resolution between a low elevation drone flight versus a higher elevation LIDAR scan.

2. Introduction and Background

2.1 Motivation

With an official population of 2.3 million people, Houston is the fourth largest city in the United States (City of Houston, n.d.) A city of such size does not come without its problems. Located in a low lying coastal region, one of the largest threats to Houston's resilience is flooding. Houston experienced a major flood event (a 100 year storm) at least once a year from 2014-2018, including named events like the Memorial Day flood, Tax Day flood, and Hurricane Harvey (Harris County Flood Control District, n.d.). Many of these events impacted the same areas repeatedly, but the recent widespread devastation that occurred with Hurricane Harvey catapulted the city into action. Hurricane Harvey occurred during my freshman year of college and flooded our family home of 18 years. While this was a catastrophic loss for my family, it ignited my passion for flood research and my goal to improve my city and protect other families from what I have been through.

2.2 Buffalo Bayou and Houston Waterways

The city of Houston is often referred to as the "Bayou City" due to the winding White Oak and Buffalo bayous that cross downtown. In Harris County alone there are 22 major watersheds directing water into over 2,500 miles of waterways (Sipes & Zeve 2012). While these watersheds have been the lifeblood of the city's growth and prosperity, flooding along the bayous has resulted in billions of dollars in damage since 2000 alone (Sipes & Zeve 2012). In this report we discuss a particular meander in Buffalo Bayou as a major case study. Buffalo Bayou runs primarily through central Harris County and has an open stream distance of 106 miles (Bayou Preservation Association, n.d.).

In 2017, Hurricane Harvey stalled over the greater Houston area from August 27 - 29, and deposited over 36 inches of rain over the area (SSPEED Center at Rice, 2020). Hurricane Harvey resulted in unprecedented widespread damage, and is one of the costliest storms in United States history (SSPEED Center at Rice, 2020). Figure 1 depicts the damage from four of the most damaging recent storms in Houston and visualizes the larger scope of Hurricane Harvey.

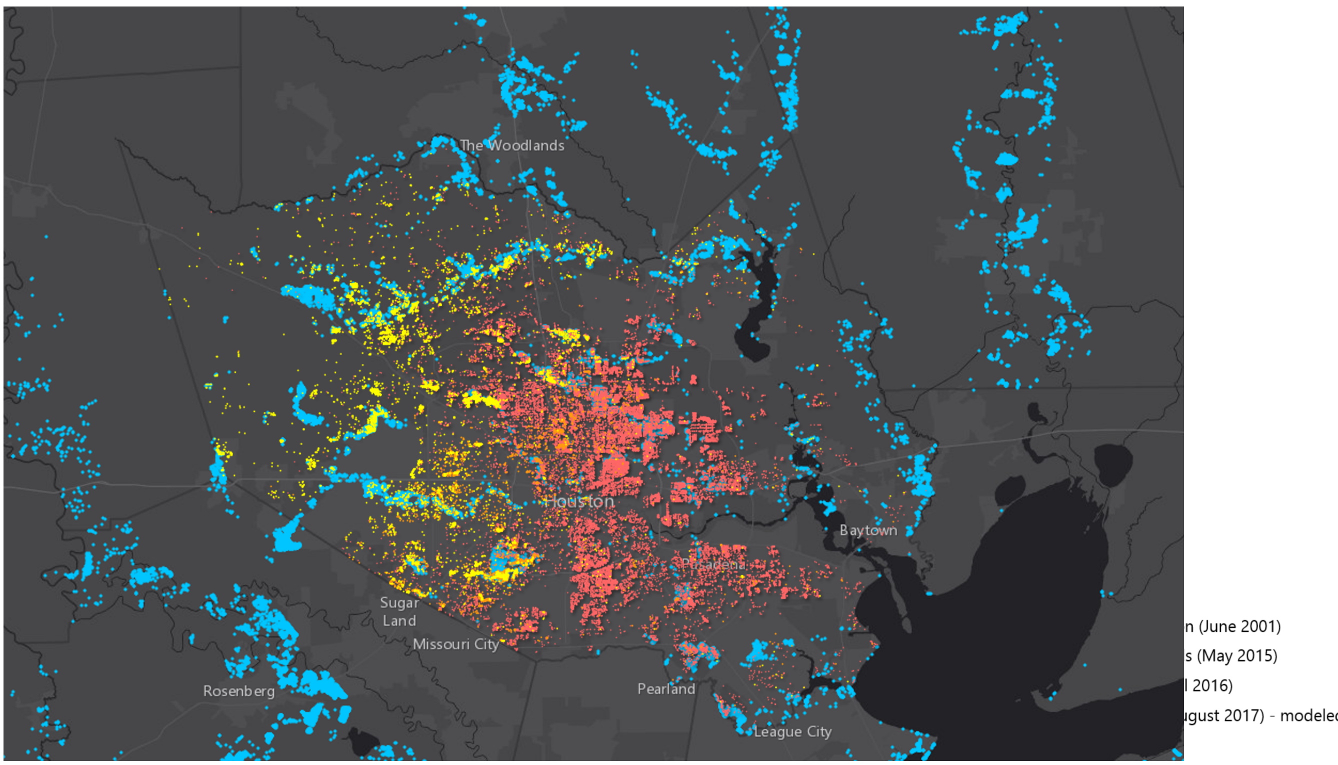


Figure 1. This map shows buildings flooded during Tropical Storm Allison, Memorial Day 2015, Tax Day 2016, and Hurricane Harvey, with Hurricane Harvey having the widest scope of flood related damage. (Houston Community Data Connections, 2018)

One year after Hurricane Harvey, voters passed a $2.5 billion dollar bond project to address flood mitigation projects across the county (https://www.hcfcd.org/2018-bond-program). Earlier that year, the Texas Water Development Board (TWDB) commissioned a statewide LiDAR dataset to be used for flood risk assessment models. However, much of the construction for the bond project has occurred since the LiDAR survey was collected. Therefore, the impact of these construction projects is not evident in the elevation data used for flood risk assessment. In order to assess and monitor the impacts of these construction projects, targeted drone photogrammetry studies should be conducted.

2.3 Microtopography and Flood Risk Assessment

Modern flood risk assessment in urban areas faces a plethora of challenges. One of the challenges is that commonly used 2D, bare-earth models struggle to address is the impact of microtopography on flood risk assessment (Backes et al., 2019). Microtopography is defined as topographic variation about a mean surface trend with amplitudes much smaller than natural terrain features (Thompson et al., 2010). Some examples of microtopography present in our data include tall vegetation such as trees, and buildings. Since microtopographic elements are much smaller than surrounding features, they often are not considered in flood models, even though they have significant impact on flood simulations (Backes et al., 2019). These features are particularly significant when studying flood patterns on a small scale (Mignot et al., 2006), such as a neighborhood or urban center. A comparative study of high resolution drone collected data and a LiDAR created bare-earth model must be done to understand the benefits and limitations of each type of data.

A team of researchers at the University of Luxembourg identified the need for this study and decided to undertake the task of comparing a drone-based DEM to a LiDAR DEM and quantifying the accuracy requirements and limitations involved in the flood modeling process (Backes et al., 2019). The study asserts that flood simulations created at a national level have a low resolution, and there is a need to create high resolution, localized models due to the nature of urban features such as buildings (Backes et al., 2019). The national scale mentioned in this study is in reference to Luxembourg or other European countries, and in our context equates to city scale. The study highlights that one of the challenges in creating an 'ideal' DEM is differences in priorities of geospatial and hydrological communities, resulting in a lack of cohesive understanding of models (Backes et al., 2019). The study area chosen contains both rural and urban elements. Datasets used in the study include a 2017 LiDAR survey with 1 m resolution and a 2019 DJI Phantom 4 Pro drone survey with 2 cm/pixel resolution (Backes et al., 2019). As part of the drone image acquisition process, the team created 70 ground control points and surveyed their elevation using RTK GPS (Backes et al., 2019). Following the processing of the drone collected images, they processed the DTM in the LISFLOOD-FP hydraulic model (Backes et al., 2019). The water depths recorded in the LiDAR DTM were higher in most areas than those reported in the drone DTM. The differences in these depths is the result of microtopography elements captured by the high resolution drone DTM (Backes et al., 2019). While it is evident microtopographic elements impact flood patterns, there is not a quantifiable direct correlation from this presented data. The study provides an interesting first attempt to document and model impacts of high resolution drone datasets on flood modeling, a field of research that should be expanded upon.

2.4 Drones as Upcoming Tools for Earth Science

In 2016, 2 million consumer drones and 110,000 commercial drones were sold (Hodgkinson & Johnston 2018). In 2018, our lab paid an initial start-up investment of $5000 for all equipment, software and insurance, and now pays roughly $300 in yearly insurance and software licensing fees. Today, the cost of the newly designed DJI Phantom 4 Pro V2 is $1600 USD (DJI Store, 2021), and yearly fees remain constant. Our lab's initial reason for purchasing the DJI Phantom 4 Pro drone was to aid Dr. Michael Thorpe's study of source to sink processes in Iceland (e.g., Thorpe et al., 2021) by creating aerial images and DEMs of the study areas, as well as identifying safe hiking paths. Since 2018, many labs at Rice have begun to consider drones as potential tools in their research. However the path from purchase to product is not clear. The capabilities of drone photogrammetry are not well documented, and many labs or individuals may be unsure if the investment is worth it for their projects. Additionally, once a drone is purchased, many groups struggle with the learning curve to operate the drone efficiently and process datasets into high-quality DEMs effectively.

The entire process, from planning image acquisition to utilizing a high-resolution DEM in GIS and HEC-HMS softwares, is documented by this study. A motivation for this project is to provide an individual or lab group who is interested in studying flooding or small scale change over time all of the information needed to assess whether a drone would be beneficial to their research, what tools are required for complete data collection, and to provide detailed methodology for reliable processing.

2.5 Our Approach

Over the course of the past three years, our lab has used drone photogrammetry to measure topography at three sites with relevance to flood management. We selected a section of Buffalo Bayou at Allen Parkway and the Police Memorial where the bayou forms a meander to be a repeat study site where we have collected three separate datasets since 2019. We also took two repeat observations over the edge of a development in Bridgeland, and did one detailed map of bedforms on a point bar in the Trinity river. In addition to these datasets we acquired the public 2018 LiDAR dataset from the state of Texas. Our regular drone flights highlight the ease of collecting change over time data of an area of interest. Differences in the digital elevation model (DEMs) of the LIDAR collected data compared to drone collected datasets highlight the higher spatial and temporal resolution of the drone datasets. This means that the drone datasets will pick up on microtopography elements and changes over time not detected by LiDAR, as seen with Backes et al 2019. On a small scale, drone photogrammetry is easy and affordable to acquire, can be reproduced to document change over time, and highlights microtopography that impacts flood risk assessment.

3. Methods

This study compiles three years of research creating a drone study framework, drone image acquisition and processing pipeline, and potential applications, with the goal of providing an individual user or lab group all information needed to assess whether a drone would be beneficial to their project. The methodology implored for each of these tasks is outlined in the following section.

3.1 Instruments

The instruments used for this study are combined from equipment owned by Siebach Lab, Raptor Aerial Services, and that used by the state of Texas.

3.1.1 Light Detection and Ranging (LiDAR)

LiDAR is a method of remote sensing typically collected from a plane that uses a pulsed laser and collection sensor to measure the distance between the source and the Earth (Texas Natural Resources Information System, n.d.). The LiDAR data used in this study is publicly available and was collected by FUGRO Geospatial, Inc. as contracted by the Texas Water Development Board (TWDB). The collection sensors used by FUGRO Geospatial, Inc. were

Riegl LMS-Q680i and Riegl LMS-Q780 (OCM Partners, 2019). A particular advantage of LiDAR is that it is not affected by vegetation or water.

3.1.2 Drone Photogrammetry

Photogrammetry is the use of imaging for the purpose of mapping or surveying. All drone photogrammetry equipment is owned by Siebach Lab. The drone is a DJI Phantom 4 Pro, flown using the corresponding DJI remote control. The flight planning software used is the Pix4Dcapture app, located on the lab Apple iPad mini. The software used to upload images and create all models is Pix4D, and analysis is performed in ArcMap 10.5 and the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS).

3.2 Processing Tools

We have streamlined the process from drone-based image planning and acquisition to final photogrammetry models or DEMs, and have also done watershed analysis in HEC-HMS as a proof-of-concept. Image collection flights are planned and acquired using the Pix4DCapture app. Images are uploaded from the drone microSD card to Pix4D to create outputs. These outputs are then uploaded to ArcGIS. LiDAR data is uploaded to ArcGIS as well. HEC-HMS is used for overland water flow and flood analysis based on terrain data from the DEM.

3.2.1 Pix4DCapture

Pix4DCapture is the app used by the lab to plan image acquisition and monitor the in-flight acquisition process. There are several drone flight apps available. Our lab tested DJI GO and DroneDeploy, however neither had the capabilities of Pix4DCapture. The first step in the workflow is to design a flight plan and download it so it can be accessed offline in the field. In the app, there are four flight modes: Single grid, double grid, circular scan, and manual mode.

The double grid is best for most of our aerial scans as it creates extensive overlap for accurate image construction. A circular scan is best used to fly around an object to collect images for a 3D model. Manual mode allows for the operator to fly the drone in any pattern and collect images when they want. Figure 2 shows a double grid flight plan of Buffalo Bayou. Other capabilities of Pix4D capture include flight time estimates, drone speed selection (for the remainder of this report we use “safe mode” speed), image overlap adjustment, and camera angle, and drone above ground level (AGL), all of which should be adjusted on a site-specific basis to collect the best images. A drone above ground level (AGL), is the vertical distance between the point of takeoff and the height at which the drone flys, the drone will stay at this elevation even though the underlying topography shifts. It is important to note that DJI GO is still required to connect the drone and the iPad, however it is not used for flight planning or image collection. A detailed tutorial video is included in the supplemental files for this thesis.

Figure 2. Screenshot from original 2/16/19 flight plan for Buffalo Bayou study site. Figure shows double grid feature, Ground Sampling Distance (GSD), adjustable flight elevation, area of flight, and estimated flight time.

3.2.2 Pix4D

Pix4D software is the first processing software used in the workflow, and is used to create an orthomosaic image, 3D point cloud, DEM, and DSM from the drone images. In order to select the right software for processing the images post-flight, we tested a variety of applications on a trial basis in 2018. Initially, the lab used Agisoft PhotoScan for processing because it was used by other labs at Rice and had an affordable standard price. However, it was not user friendly or streamlined. Each output (ortho image, point cloud, DEM) required separate processing and the repetition of previous steps. This was tedious, time intensive, and created increased opportunity for error. Furthermore, Agisoft does not have its own flight software app for the iPad, so we had to test three other apps and each had some advantages and disadvantages. This led us to consider other options. While initially skeptical of Pix4D due to its much higher standard cost, we decided to run a trial phase to test its capabilities. Pix4D is widely used within the drone industry, has robust tutorials, and many active troubleshooting forums. In the trial phase, we learned Pix4D has a streamlined processing flow, more output options, and better user interface. It also has a connected app for flying the drone with nearly all of the features we had found helpful in other app tests. Our lab was able to secure an educational discount, thus making our final decision easy.

There are several key processing advantages to Pix4D. The first is the ability to manipulate processing options. There are three steps in processing a project: (1) Initial, (2) Point Cloud & Mesh, and (3) DSM, Ortho & Index. Step 1, Initial, uploads all drone images to the project and ties them together to create the orthomosaic image. In step 2, Point Cloud & Mesh, it is important to check the box “classify point cloud” so that points will be automatically labeled as ground, road surface, high vegetation, building, and human made object. Once the point cloud is created, the user can manually classify the point cloud and choose to remove a group if desired. This is valuable in the case where the user wants to remove trees or human made objects for a “bare earth model.” Steps 1 and 2 can be run simultaneously. The final step, DSM, Ortho & Index, allows the user to create a geoTIFF file, a digital terrain model (DTM), or a contour map.

An additional processing advantage of Pix4D are the quality reports (QR). After each processing step, Pix4D automatically generates a QR, detailing the accuracy of the step. In step 1, the QR provides the mean reprojected error which is the image projection accuracy, which should be less than 0.5 for best results. The QR also identifies all key points used to create the orthomosaic image. In an accurately stitched image, this section should include lots of balck lines indicating that each point was tied across multiple images.

Tips for image acquisition and efficient Pix4D processing are included in the supplemental files for this thesis.

3.2.3 ArcGIS

ArcGIS is world-renowned for calibration, manipulation, and analysis of created DEM and DSMs. In this study, we used ArcMap 10.5.1. Specific details of processing steps for different mosaics are included in later sections.

3.2.4 HEC-HMS

The Hydrologic Engineering Center’s Hydrologic Modeling System (HEC-HMS) software simulates all hydrologic processes of watershed systems (US Army Corps of Engineers, n.d.). The software is free and widely used around the world.

3.3 Datasets

The datasets included in the research are from several different sources. Some were developed by the lab and others through outside organizations.

3.3.1 Texas LiDAR Survey

The LiDAR data used in this study is publicly available and was collected by FUGRO Geospatial, Inc. as contracted by the Texas Water Development Board (TWDB) (OCM Partners, 2019). The survey was commissioned by the Houston-Galveston Area Council (H-GAC), who have commissioned four Texas coast LiDAR scans since 2006 (Houston-Galveston Area Council, 2021). The data is separated into UTM zones, with the H-GAC area falling in UTM Zone 15 N and UTM Zone 14 N. Within each zone, the data is divided into tiles. Our area of interest is covered by tile 2995134. This data is publicly available and was accessed for this study via the Rice University GIS Data Center.

3.3.2 Buffalo Bayou Meander at Harris County Police Memorial

The main area of interest for our study is a section of Buffalo Bayou at Allen Parkway and the Police Memorial. Since 2018, we have completed three aerial scans of the area. All three flights were flown using the same flight plan, created in the Pix4Dcapture app. The flight area is centered around the location 29.736°, -95.384°, has an overlap of 74%, camera angle of 65°, AGL of 76.2 m (250 feet), and a double grid area of 0.177 km^2 (43.76 acres). The total time for the double grid flight is around 37 minutes, and requires two batteries to complete. The takeoff/landing site was located on the bayou point bar on the east side of the bridge for each flight. Each flight collected 580 images.

After each flight, the images were saved to the lab computer in a folder where all flight specific outputs were stored. In Pix4D, a new project was made for each flight. Then, the folder where the images were saved to was selected, automatically uploading all photos. The software automatically identifies the coordinate system, but it can be changed if desired. Finally, the user selected the type of processing they wished to complete. For our study, we used the standard 3D map template, which produces an orthomosaic, DSM, 3D mesh, and point cloud.

3.3.3 Bridgeland Development

We selected the bridgeland subdivision, located in Northwest Houston, as a site for drone study after discussions with Jim Blackburn at Rice University and Auggie Campbell of the West Houston Association. They recommended this location as an area of interest in March 2019 as it was undergoing the final stages of subdivision completion and scheduled for additional construction in the near future. Our area of study was the back of the subdivision next to Cypress Creek, where there were houses in the final stages of construction and a large open field that was affected by the ongoing development. This area was too large to create a single drone flight, so we decided to split it into two halves that would be stitched together in Pix4D. We collected two datasets of this area one year apart, the first in September 2019, the second in September 2020. Between the two years, the parameters of the designed flight are the same, but more images were collected in 2019 than 2020 due to different battery strategies. Both years ended up with mostly single-grid coverage and a few lines of coverage in the perpendicular direction. The southern half is 1.39 km^2 (344.43 acres), AGL of 96.01 m (315 feet), image overlap of 74%, and a camera angle of 65°. In 2019 1108 images were collected and in 2020 808 images were collected. The northern half has an area of 1.39 km^2 (344.43 acres), flown at an elevation of 96.01 m (315 ft) with an overlap of 74%, and camera angle of 65°. In 2019 997 images were collected, and in

2020 808 images were collected. In 2019, batteries were used past the recommended percentage and the drone disconnected from the device around 15% remaining battery. In 2020, two batteries were used per flight and not used past 25%.

3.3.4 Trinity River

In August of 2019, our lab group went on a field trip with another lab from Rice University to their study site at the Trinity River. Their objective was to create a high resolution dataset of bedforms on the point bar of a meander in the river. Our flight was a double grid with 74% overlap, an area of 0.22 km² (54.66 acres), a camera angle of 65°, with an AGL of 51.82 m (170 feet).

3.3.5 White Oak Bayou - Raptor Aerial Services

In 2018, Mike Allison of Raptor Aerial Services was contracted to create an elevation model of White Oak Bayou near Jersey Village. The survey area was 1.10 km² (273 acres), and the flight parameters were an AGL of 76.2 m (250 ft), and 80% overlap. The area was split into three sections and covered using a double grid flight pattern.

3.4 Data Processing

After the drone images were processed in Pix4D, the resulting DEMs were uploaded to ArcMap 10.5.1 to enable comparison between datasets. The Texas LiDAR DEM was also uploaded to GIS at this step.

3.4.1 Buffalo Bayou GIS Processing

First, the two Pix4D DEM .tiff files were uploaded to the GIS project. To add the Texas LiDAR data required connecting to the Rice GIS Data center network. To do this, I was aided by

Jean Aroom from the Rice University GIS Data Center. Once the network connection was established, we navigated to the folder location LiDAR > LiDAR_2018_HGAC_Fugro_CoastalTexas > Hydro_Flattened_DEM > UTM15 and selected stratmap18-50cm-2995134. This tile was added to the project. The LiDAR projection needed to be updated to match the drone DEM projection.. Next, the LiDAR data was in the shape of the complete tile and needed to be clipped to the extent of the drone flights to compare elevation differences over the same area. This was achieved by creating a shapefile of the 2021 boundary. Then, the LiDAR could be clipped to the size of the shapefile.

The remaining issues were the discrepancies in baseline reported elevation between the 2019 and 2021 drone flights and between the drone flights and LiDAR. Between the 2019 and 2021 drone flights, there was an elevation discrepancy of 50 feet. While some difference is expected due to construction and surface change, this was clearly an error. To calibrate the elevation, we decided to identify known points that would not have changed in elevation between the three years, and adjust accordingly. The location identified was the centerline of Allen Parkway. This location was chosen because it is far enough in from the edge of the flight that it has reliable drone resolution, is visible in all three datasets, and has not experienced construction during the study period. First, we realized that the LiDAR elevation was reported in meters and the drone elevation was reported in feet. We converted meters to feet using the fields calculator in the attribute table. Then, in the clipped LiDAR layer, we placed six points evenly spaced along the centerline of the parkway and calculated the average elevation of these points. We then compared the elevation in feet at each point between the LiDAR, 2019, and 2021 layers to determine by how much the 2019 and 2021 elevations needed to be adjusted. Once the elevations were calibrated, elevation difference maps could be computed for 2019 vs 2021, 2018 vs 2019, and 2018 vs 2021. This was done using the Spatial Analyst Minus tool.

3.4.2 HEC-HMS

The software HEC-HMS is used to model flow of water through a watershed. The source for terrain data in HEC-HMS is commonly a DEM, produced from LiDAR data. A drone produced DEM can be used as terrain data and uploaded without additional steps or modifications. The process to upload a DEM to a HEC-HMS project is Components > Terrain Data Manager > New and navigate to the DEM file, select the proper units and click finish. Once the terrain data is added to the project, it can be linked to the basin model to delineate subbasin and reach elements (Hydrologic Engineering Center, 2021). We made a HEC-HMS model for one of our drone runs as a proof-of-concept, although we do not report the results here because some parameters were selected incorrectly, rendering the model inaccurate.

4. Results

4.1 Logistical Tradeoffs

Since 2006, H-GAC has commissioned four LiDAR projects (Houston-Galveston Area Council, 2021) and have cost the state $20.4 Million since 2009 (Texas Natural Resources Information System, n.d.). The Texas Coastal Project, the section of the statewide LiDAR survey used for this study, was completed between January 12 and March 22, 2018, and the data was made publicly available in early 2019 (OCM Partners, 2019). The LiDAR DEMs have an average resolution of 1 m/pixel and occur every ~5 years, providing an incredible statewide dataset for observing large-scale change over time.

The initial cost of the drone and all associated equipment and software was $5000, but this cost is now stable except ongoing drone insurance of ~$150/yr and Pix4D license renewals at ~$200/yr.

Prior to beginning a drone flight, it is important to review FAA regulations and check that the project area is safe to fly. It is important to identify any nearby airports or helicopter landing pads. FAA regulations currently prohibit any drone flights within 5 miles of an airport or at a height of above 400 ft (Federal Aviation Administration, 2018).

Our lab completed a flight of the Buffalo Bayou study area for three consecutive years, resulting in three separate DEMs. The Buffalo Bayou location double grid flight plan has an area of 0.177 km^2 (43.76 acres) with an average Ground Sampling Distance (GSD) of 2.41 cm/pixel (0.95 in/pixel). The average flight time for the Buffalo Bayou study area is 37.14 minutes, and the Pix4D to DEM processing takes one operator one day to complete. This size area required two batteries, with the first being used until 25% remained and the second not being fully used. The on-ground resolution of the orthomosaic and for the DEM is 2 x GSD, which is 4.82 cm/pixel (1.8 in/pixel). Total Pix4D processing took 02:12:59.

The Bridgeland project had a larger total area because it consisted of two flights stitched together. For the total flight plan area, both halves combined, was 1.39 km^2 (344.43 acres) with an average GSD of 3.02 cm/pixel (1.19 in/pixel). Due to battery limitations, two batteries were allotted for each half. The on-ground resolution of the orthomosaic amd for the DEM is 2 x GSD, which is 6.05 cm/pixel (3.8 in/pixel).

The Trinity River survey had an area of 0.23 km^2 (54.66 acres) with an average GSD of 1.88 cm/pixel (0.74 in/pixel), and a flight time of 32 minutes. The time for step 1, initial, processing was just over 1 hour. The on-ground resolution of the orthomosaic amd for the DEM is 1 x GSD, which is 1.88 cm/pixel (0.74 in/pixel).

4.2 DEM Quality

For the Buffalo Bayou Project, drone photogrammetry was used to produce two DEMs. Based on the quality reports from Pix4D, each image had a median of 22,298 keypoints, so we were able to obtain extremely high quality surface maps. The third DEM was created using LiDAR.

4.2.1 Actual resolution

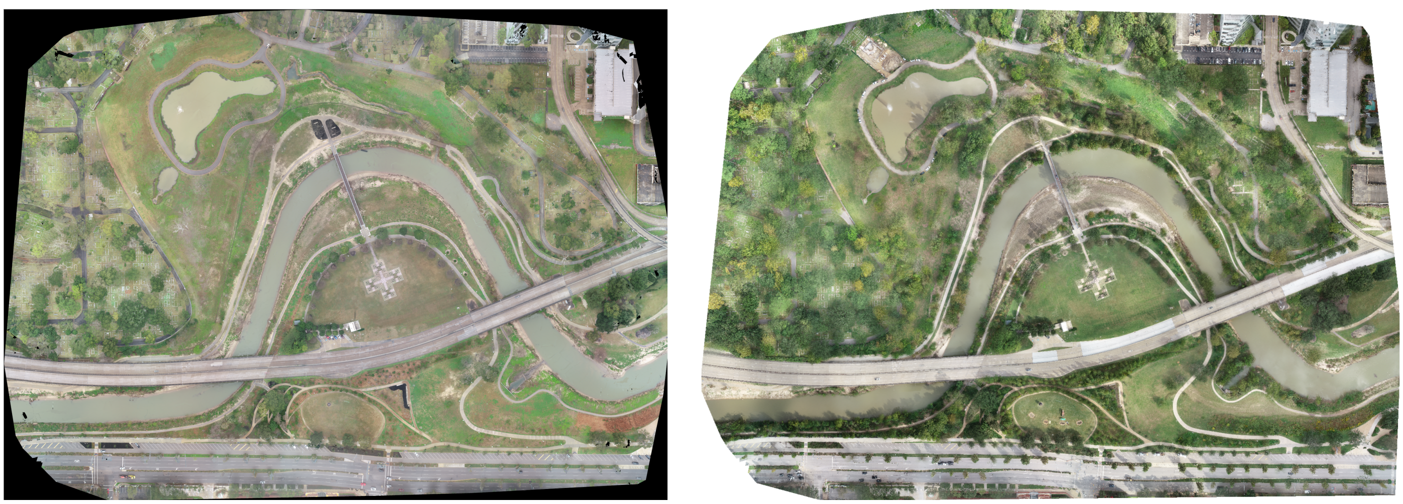
Resolution is a result of a flight's AGL and area covered. Resolutions of drone-based datasets are reported as the flight recorded ground sampling distance and the Pix4D reported orthomosaic and DEM resolution. The resolution data produced by this study can be found in table 1.

Table 1. Spatial resolution of drone photogrammetry datasets

	Buffalo Bayou	Bridgeland	Trinity River	White Oak Bayou (M. Allison)
Drone Above Ground Level (AGL)	76.2 m (250 ft)	96.01 m (315 ft)	51.82 m (170 ft)	76.2 m (250 ft)
Area Covered	0.177 km²	1.39 km²	0.22 km²	1.10 km²
Average Ground Sampling Distance (GSD)	2.41 cm/pixel (0.93 in/pixel)	3.02 cm/pixel (1.19 in/pixel)	1.88 cm/pixel (0.74 in/pixel)	2.286 cm/pixel (0.9 in/pixel)
Orthomosaic and DEM Resolution	4.82 cm/pixel (1.8 in/pixel)	6.05 cm/pixel (3.9 in/pixel)	1.88 cm/pixel (0.74 in/pixel)	N/A

4.2.2 Vegetation

Initially, only two flights over the Buffalo Bayou meander were completed, one in February 2019 and a second in September 2020. The flight plans for these two flights were identical. The resulting orthomosaic images are seen in figure 1. Fig 1A is the orthoimage from the 2019 flight, 1B is from 2020. There is a significant tree cover difference between the two times of year, so this set of images became a useful point of reference for understanding the seasonal and vegetation-related limitations of drone photogrammetry. The trees caused significant changes in the DEM, making it difficult to isolate ground surface elevation change.



A. February 2019 Ortho Image

B. September 2021 Ortho Image

Figure 3. Figure 1 consists of two orthomosaic images from 2019 and 2020 drone flights and depicts seasonal tree cover differences.

4.2.3 Point Bar Bedforms

The drone flight from the Trinity River focuses on point bar bedforms. Figures 4A and 4B compare the orthomosaic created by Siebach Lab to the orthomosaic created by Dr. Chenliang Wu, which both provide an aerial view of meter-scale bedforms located on the point bar. Figure 4C is the DEM created by Dr. Chenliang Wu, which had a resolution of 3.07 cm/pixel, and further highlights the presence of bedforms.

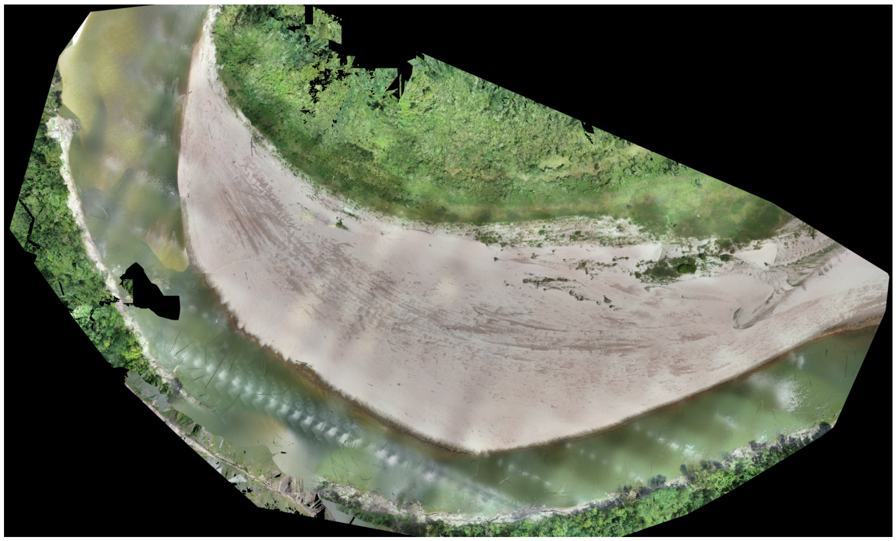


Figure 4A. Pix4D processed orthomosaic image created by Jessica Sheldon of the point bar at Trinity River Moss Hill study site.

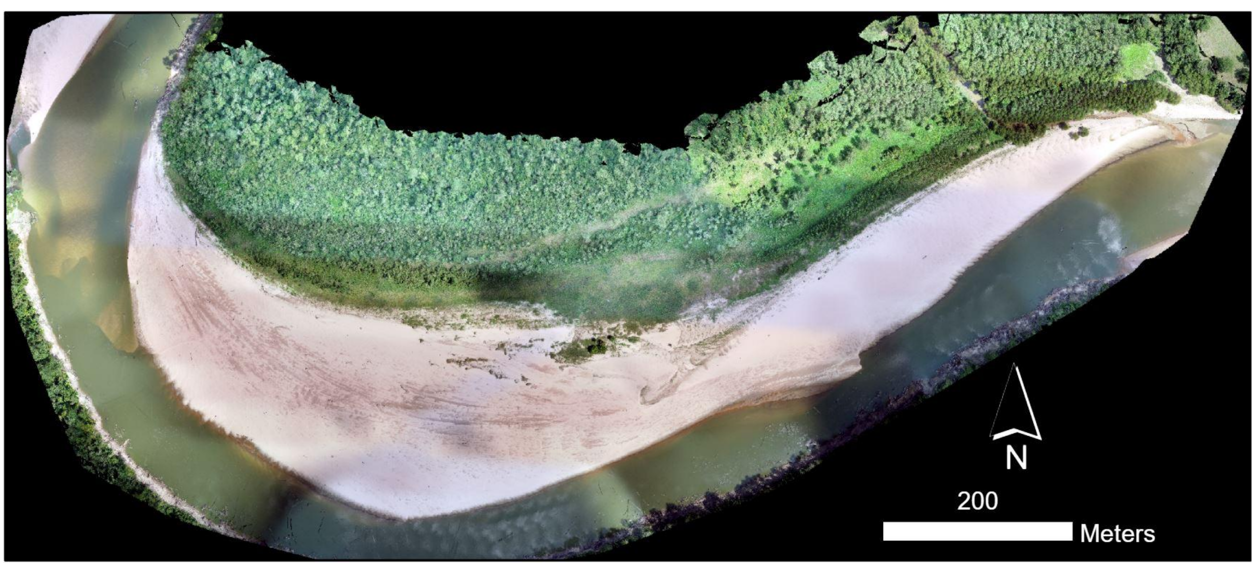


Figure 4B. Pix4D processed orthomosaic image created by Dr. Chenliang Wu of the point bar at Trinity River Moss Hill study site. Courtesy of C. Wu.

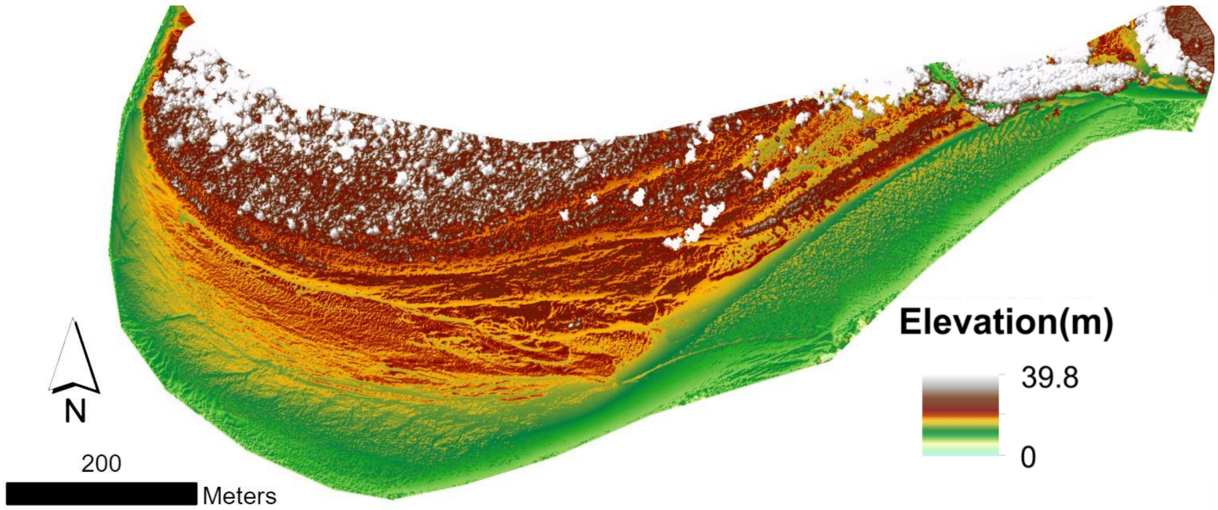


Figure 4C. DEM created by Dr. Chenliang Wu of the point bar at Trinity River Moss Hill study site. Courtesy of C. Wu.

4.3 DEM Differencing

To identify resolution differences and changes over time, DEMs from repeated studies were compared in GIS. To identify change over time in White Oak Bayou, a drone-based DEM was used to compare anticipated channel bed elevation to observed channel bed elevation.

4.3.1 Buffalo Bayou

Calibrated DEMs of 2018 LiDAR, 2019 drone, and 2021 drone data over Buffalo Bayou were compiled in GIS for comparison to each other. From those DEMs, three difference maps were created in GIS to observe change over time at the Buffalo Bayou meander site. Figure 5A, B, and C are individual DEMs. Figure 6A, B, and C are DEM difference maps.

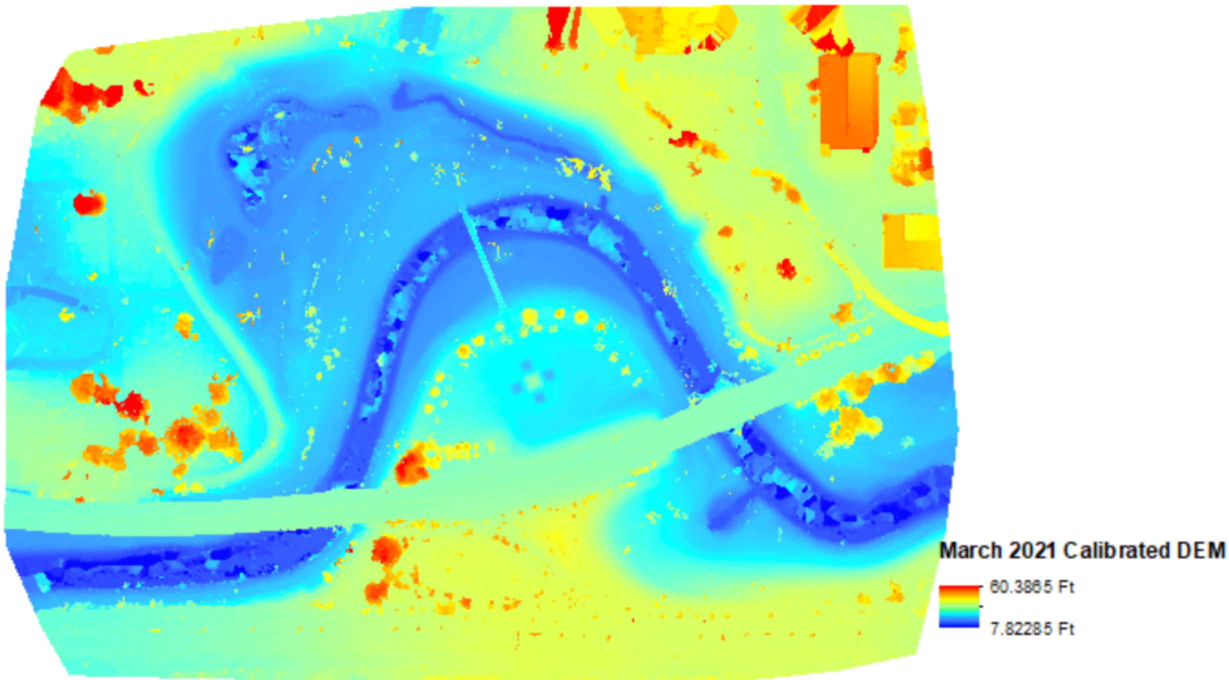


Figure 5A. March 2021 calibrated DEM

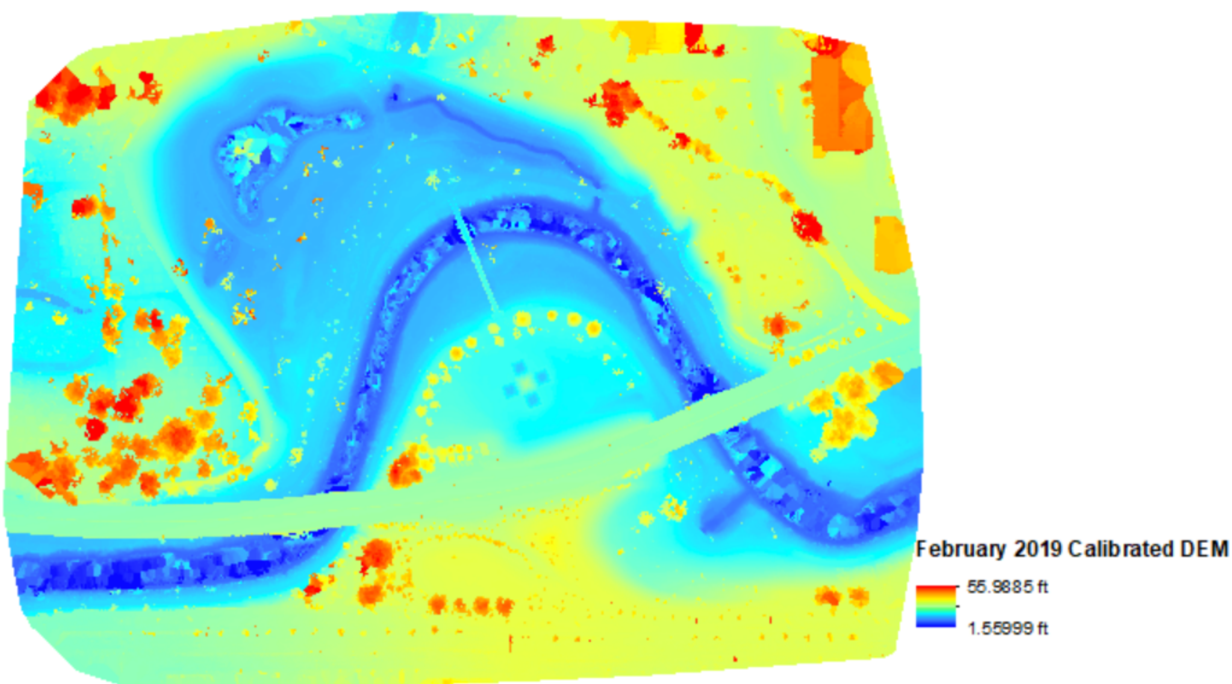


Figure 5B. February 2019 calibrated DEM

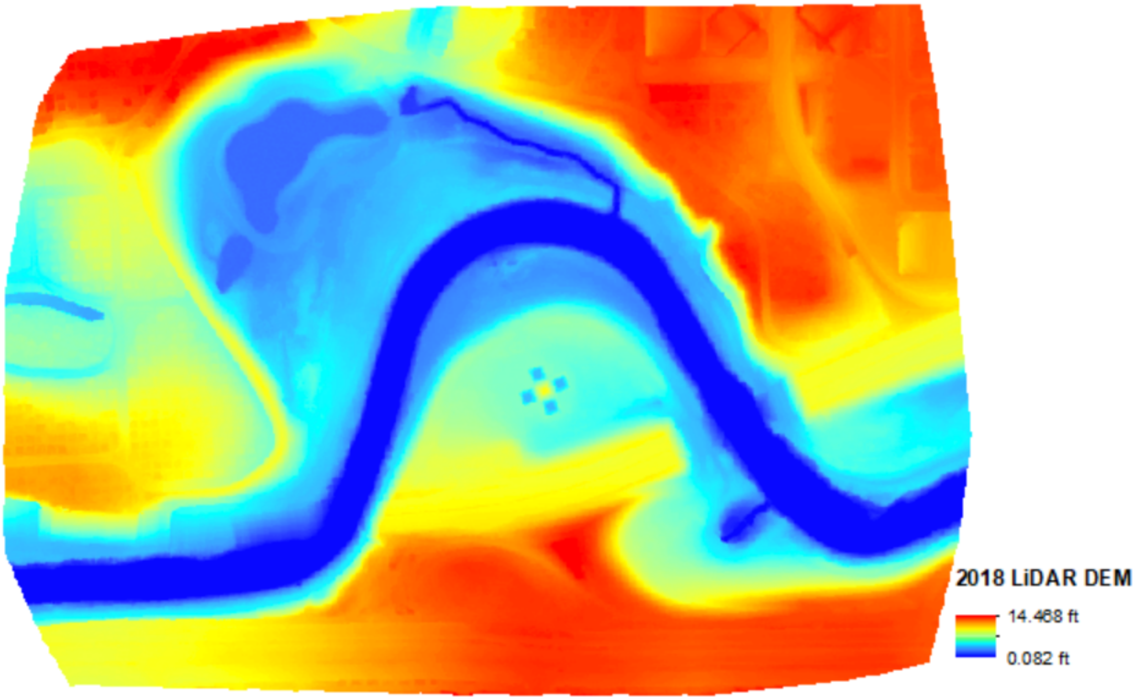


Figure 5C. 2018 LiDAR “bare earth” DEM

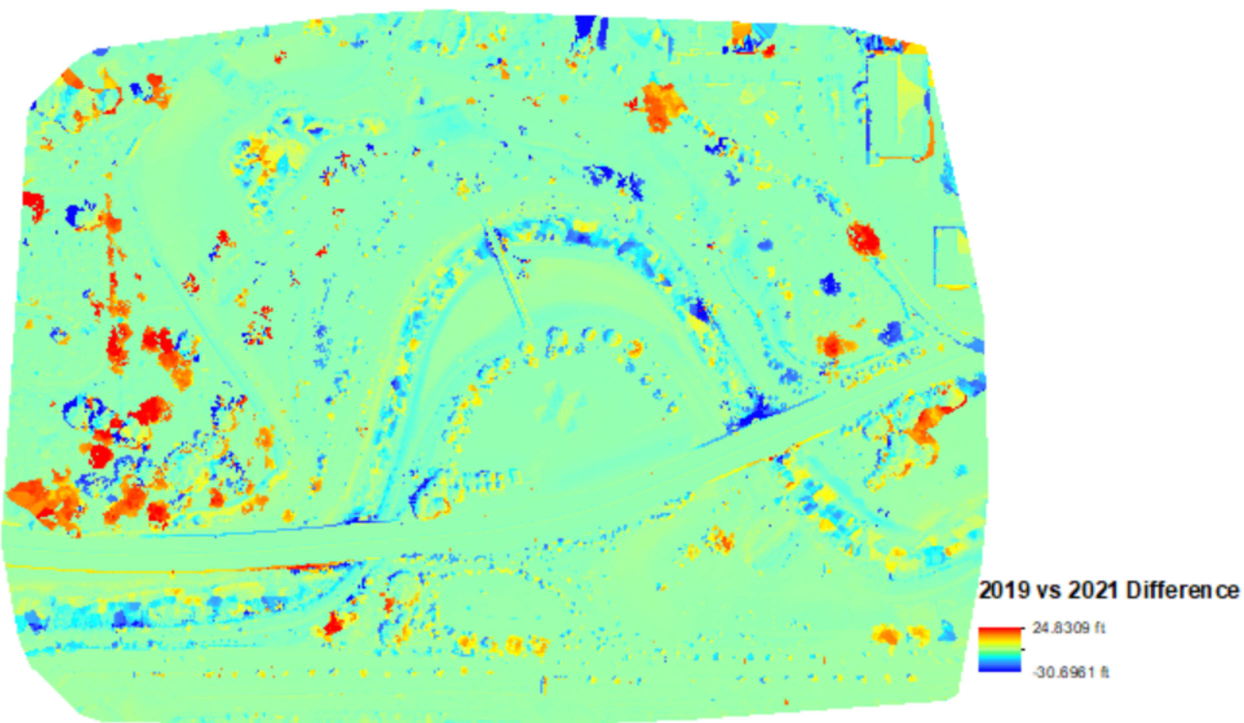


Figure 6A. GIS created difference map. 2019 calibrated DEM vs 2021 calibrated DEM.

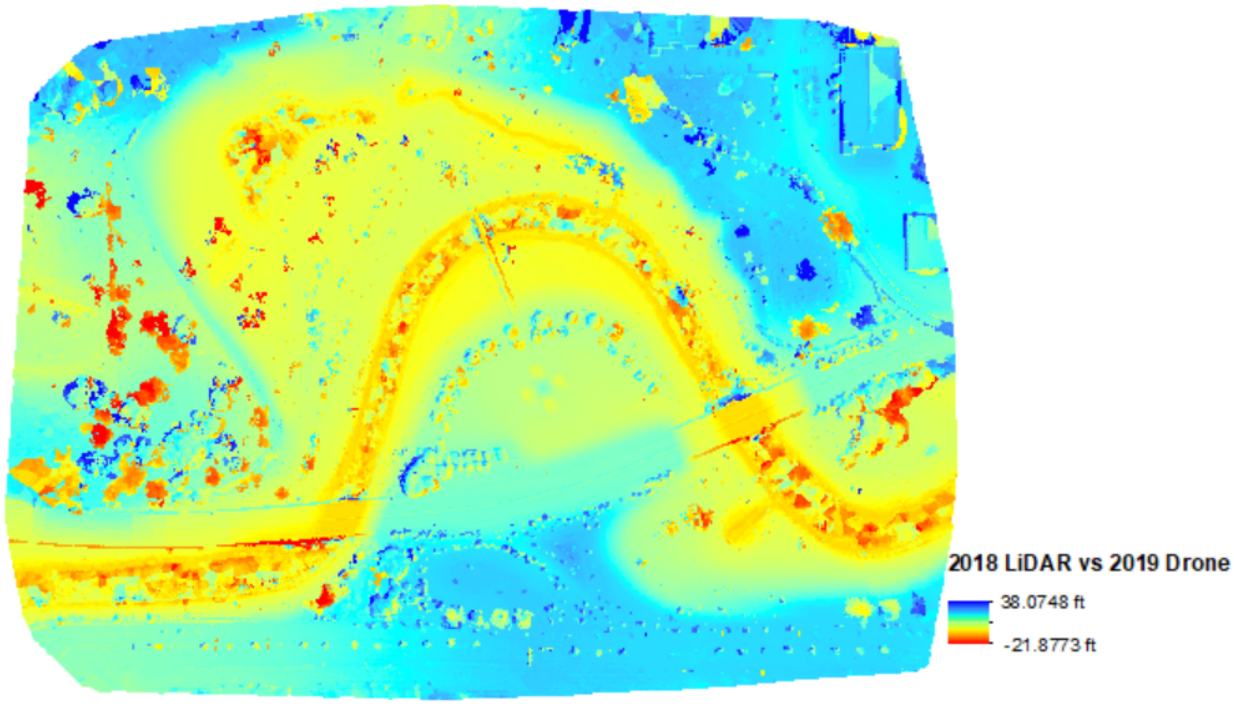


Figure 6B. GIS created difference map. 2018 LiDAR DEM vs 2019 calibrated DEM.

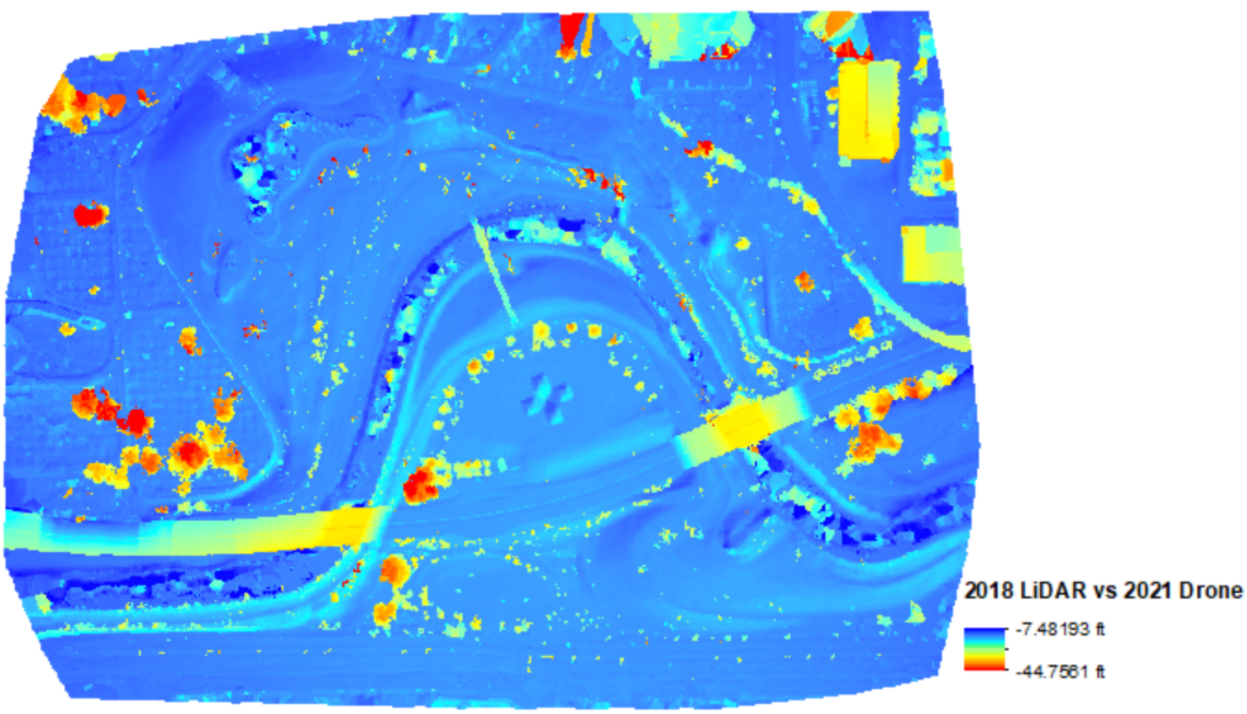


Figure 6C. GIS created difference map. 2018 LiDAR DEM vs 2021 calibrated DEM.

4.3.2 White Oak Bayou

Drone photogrammetry was utilized by Mike Allison to create a DEM for the White Oak Bayou project area, as seen in Figure 7A. This DEM was used to create a channel profile of the channel bed elevation, as seen in Figure 7B.

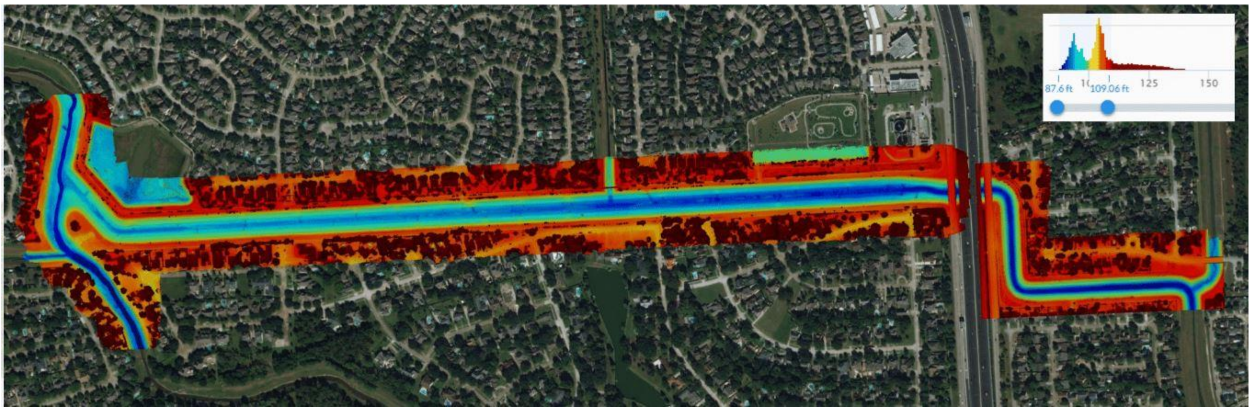


Figure 7A. Geolocated DEM of White Oak Bayou project. Courtesy Mike Allison.

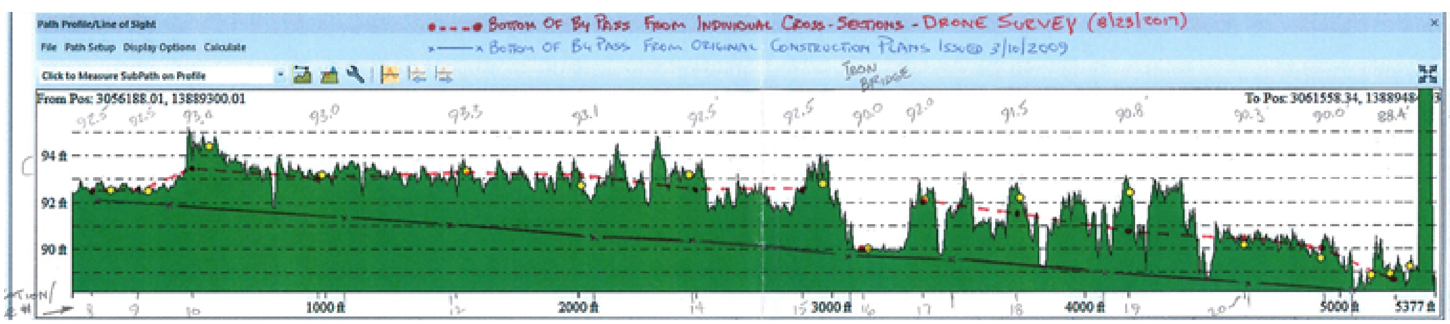


Figure 7B. Channel grade profile, created by Mike Allison. Lower blue line indicates originally designed channel elevation. Dashed red line indicates average observed channel elevation, as calculated from drone DEM. Courtesy Mike Allison.

5. Discussion

The results of this research help clarify the variety of applications for drones in the field of environmental science flood related research. Specifically, we describe three locations we have monitored with a single inexpensive Phantom 4 Pro drone and the processing pipeline we have developed for drone photogrammetry to show the advantages and disadvantages of a user or lab purchasing a single drone to monitor topographic changes related to flood history and flood management. We provide detailed examples of applications for drone photogrammetry and the extent of its capabilities.

5.1 Resolution versus Coverage

According to our data, when planning a drone flight, there are five main factors to consider: coverage area, ground resolution, time for flight, above ground level, and batteries required. To maximize one of these factors is often at the expense of another. Table 2 compiles a list of these factors across three coverage areas and adjusts the AGL. Flight time is dependent on both coverage area and AGL. Ground resolution (GSD) is dependent on AGL. Number of batteries is estimated based on our lab experience. For this table, it is assumed all flights are a double grid and all batteries are fully charged. Single grid flights would take roughly half the time, but would have a lower resolution.

Table 2. Resolution versus coverage comparative chart. Chart compares 3 coverage areas (small, medium, large) with the impact of changing AGL.

Coverage Area	Ground Resolution	Time	Above Ground Level (AGL)	Batteries
0.067 square km	2.3 cm/pixel	16 min	76.2 m (250 ft)	1 battery
0.067 square km	1.83 cm/pixel	22 min	61.0 m (200 ft)	1 battery
0.177 square km	2.41 cm/pixel	44 min	76.2 m (250 ft)	2 batteries
0.177 square km	1.83 cm/pixel	50 min	61.0 m (200 ft)	2 batteries
0.38 square km	2.54 cm/pixel	53 min	84.73 m (278 ft)	2-3 batteries
0.38 square km	2.3 cm/pixel	1:05 hr	76.2 m (250 ft)	3 batteries
0.38 square km	1.83 cm/pixel	1:40 hr	61.0 m (200 ft)	5 - 6 batteries

5.2 Site Content

Our collection of projects completed for this study span a variety of subject matter. This includes highly vegetated areas, water, and urban areas. None of these locations prohibited drone photogrammetry outright. However, there are limitations of drone photogrammetry in these situations that must be taken into consideration by the operator.

5.2.1 Vegetation

Originally, our Buffalo Bayou study consisted of only two flights, one from February 2019 and the second from September 2020. As previously mentioned, the flight plans for these flights were the same, but the orthoimages and DEMs have striking differences. The difference is not solely from newly planted trees, but from increased tree cover due to seasonal processes. February is the middle of winter and trees and shrubs are leafless. In September, trees and plants are at full coverage, which created a seasonal discrepancy. When planning a drone flight, it is important to take this into consideration. This is not the case with LiDAR, which creates a bare-earth DEM that completely excludes trees. Yet, the Texas LiDAR project still made sure to fly the LiDAR instruments in the winter, January to March 2018, during the leaf offseason (OCM Partners, 2019).

5.2.2 Water

Most of our projects, especially Buffalo Bayou and Trinity River, feature a major water element. A limitation of drone photogrammetry is its inability to accurately capture elevation of surface water. Pix4D explains that the difficulty with water is that it is both moving and reflective, two of the three categories they recommend limiting in your images. Moving subject matter is not constant between images, reducing the number of key points generated and thus reducing the accuracy of the model. High reflectivity results in poor exposure which also impacts the processing. These water-related issues are visible in the drone produced DEMs. In figures 4A and 4B, the blocky elevation gradient along the bayou is not change in elevation but is Pix4D struggling to model the surface of the bayou. That said, if this is a concern for a photogrammetry model with a water-related purpose, the water elevation can be extrapolated to a specified value during processing in Pix4D (e.g., the user can extrapolate a shoreline elevation across the water feature) or the user can edit the point cloud to remove unwanted water points.

5.2.3 Buildings

If a study site is in an urban area, the user may want to create a DEM with buildings or man-made objects. A benefit of drone photogrammetry in combination with Pix4D processing is the ability to edit the point cloud, and thus impact resulting DEMs and DSMs. As mentioned in section 4.2.2, in step 2 of processing there is the option to “classify point cloud,” resulting in the software classifying points as ground, road surface, high vegetation, building, human made object, and/or unclassified. After this step has completed processing, the user can manually edit point classifications of the point cloud. In the editor, the user can select items to be removed manually. The resulting point cloud of manual point cloud assignment can be seen in Figure 7. Once all points are assigned, the user can complete processing step 3, but a new output will be generated know as a Digital Terrain Model (DTM) where ground and road surface classes are unaltered and smoothing is applied to Unclassified, High Vegetation, Building and Human-Made Objects (Pix4D, 2018). The resulting DTM is similar to a LiDAR bare-earth DEM. It should be noted that due to the smoothing process, the DTM resolution will be slightly lower than the project (Pix4D, 2018).

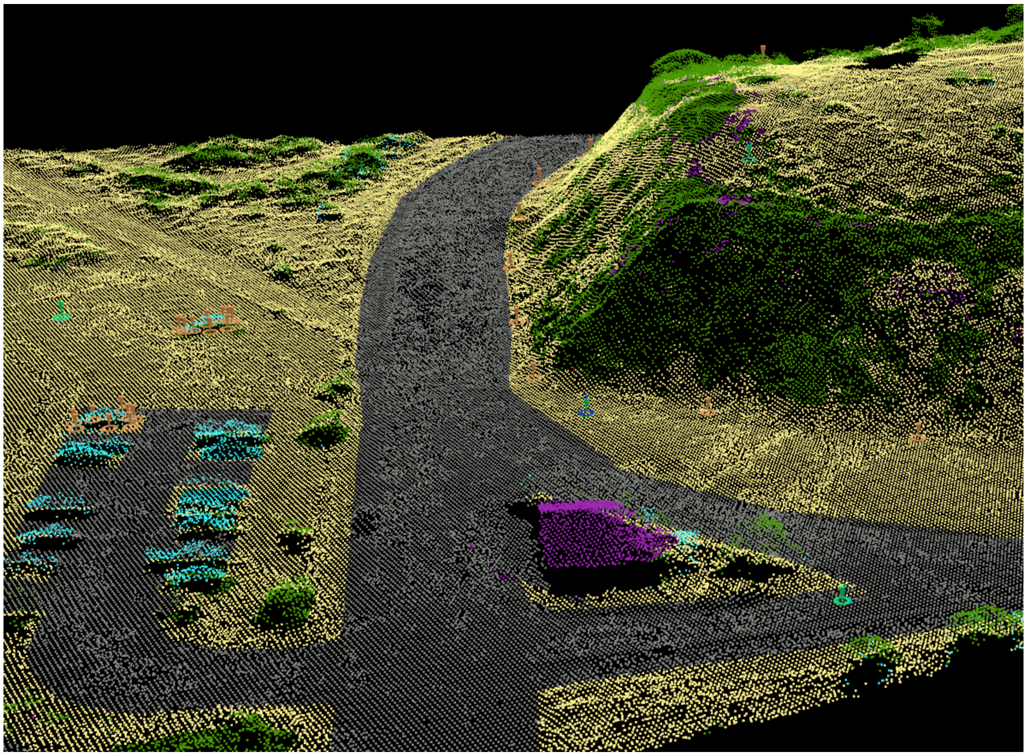


Figure 7. Complete classification of a point cloud. Initial classification was generated by Pix4D and then edited by Jessica Sheldon. Yellow represents ground, green is high vegetation, gray is road surface, purple is man-made object, and blue is unclassified which in this model indicates vehicle.

5.3 Types of Projects that Would Benefit from Drone Photogrammetry

Currently, the majority of projects that involve modeling or elevation inquiry rely on LiDAR. LiDAR, as our study shows, produces high resolution DEMs that are reliable for many projects. However, when undertaking a project on a small scale, area, or timeline, there are clear benefits of drone photogrammetry.

5.3.1 Construction and Intentional Change

One type of project that benefits from drone photogrammetry is monitoring construction and intentional surface change. This can be seen in our Buffalo Bayou study. Between 2018 and 2021 when the datasets were collected, this section of the bayou underwent major construction, including creation of buildings, pond expansion, tree planting, and more for regular maintenance and for channel maintenance by Harris County Flood Control district. Our drone surveys capture this change with a comparatively inexpensive and repeatable process. Because airborne LiDAR is so expensive, it cannot be done regularly and must be done on a large scale to make it cost efficient, which increases the time for collection and processing of data. These factors inhibit LiDAR from regular use to assess elevation changes created by a construction project. Regular drone photogrammetry-based monitoring of construction areas and occasional input of the DEMs into a modeling program like HEC-HMS would allow higher spatial and temporal resolution updates to flood zones and flood risk as well as monitoring progress towards surface change objectives.

5.3.2 Temporal Change Due to Flooding or Natural Causes

A case study where drone photogrammetry was used to identify unanticipated temporal change is in Mike Allison's study of White Oak Bayou near Jersey Village (Allison, 2018). Following the construction of a bypass along White Oak Bayou, residents contacted Allison as they believed the project was increasing the area's flood risk. The residents wanted Allison to create a DEM of the channel to determine the bed elevation and compare it to what Harris County Flood Control District believed it to be. The project was ideal for drone photogrammetry because it was a small scale, urban study area that had undergone construction. Allsion used a DJI Phantom 4 Pro drone, real time kinematics GPS, and 18 ground control points to collect the data. From the resulting DEM, Allison was able to create a channel bed profile that indicated a 1.5 foot higher bed elevation than designed by HCFCD. The bypass had impacted the bayou flow rate which led to increased silting of the downstream channel. The findings were presented to the city and resulted in the channel being desilted by HCFCD (Allison, 2018). Drone photogrammetry was critical in this neighborhood documenting their change in flood risk to receive municipal action.

5.3.3 Observations of Microtopography Relevant to Fluid Flow

The high resolution of drone imagery and DEMs enables observation of small-scale surface features. In the Trinity river project, we were able to observe and map individual subaqueous dune bedforms preserved on a point bar. These bedforms are evident in both the orthomosaic images and the DEM. Mapping of these features allowed graduate students in Dr. Jeff Nittrouer's group in the Rice University Department of Earth, Environmental, and Planetary Science to estimate past river flow and describe flood events that formed the bedforms. Bedforms occur at the interface of fluid and sediment, in this case is a river and the bank.

6. Conclusion

Over the past three years, I have researched how drones can be applied to better understand flooding. This initial goal led me down several paths, including learning several image processing softwares, how to fly a drone, how to best utilize our image processing software, applications of GIS for comparing elevations, and how drone photogrammetry can be applied to assess flood risk. All together, my research can best be summed up as a framework for assessing the utility of drones for a given project. This framework, as outlined in this thesis, should be applied by an individual or lab group interested in studying flood risk and or change over time in a small study area. The framework provides cost benefit analysis of drone startup fees, detailed instructions on how to prepare a drone flight and process collected images, how to create models and assess the accuracy and resolution of those models, and the types of projects that would benefit from drone photogrammetry. My goal with the publication of this thesis is for future individuals and lab groups to not endure the same learning curve that we experienced, and to be able to hit the ground running with applied drone research. Drones provide an opportunity to expand our understanding of flood assessment and surface change over time, and hopefully this thesis provides individuals with the background information needed to see the benefit of a drone in their work and make strides in flood mitigation in the city of Houston and other flood prone areas.

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