Analyzing the Vulnerability of Buildings to Coastal Flooding in Galveston, Texas

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In Partnership with Gulf of Mexico Alliance Community of Practice

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ABSTRACT

This study provides the first data-driven coastal flood risk analysis for buildings in Galveston, Texas. The U-Surge database provided high water marks for 93 hurricanes and tropical storms since 1900, which were converted to NAVD88 datum. A log-linear regression analysis (Gumbel Distribution) provides return levels for the 500-, 200-, 100-, 50-, 25- and 10-year storm tide events, as well return frequencies for the 1900 Storm and Hurricane Ike (2008). These water levels were increased by sea level rise projections from NOAA (2017), providing extreme water level estimates for the years 2000, 2020, 2050 and 2100. We pioneered an innovative methodology to use Google Earth and Google Street View images to estimate First-Floor Elevations (FFE) above ground level for 479 buildings across 40 city blocks. These elevations were added to ground elevation above NAVD88, obtained from Digital Elevation Models (DEM) through the United States Geological Survey (USGS) viewer for The National Map. Extreme water levels were superimposed upon a scatterplot of FFE distribution. This analysis determined that high-magnitude/ low-frequency events will approach 100% building inundation by the second half of the century, with the 100-year flood inundating 70% of the buildings by mid-century and 99% by end of century, with intermediate-high sea-level rise. Flood inundation from the 10-year flood increases from 0-11% between the years 2000-2050, but then accelerates from 11%-59% between the years 2050-2100, with intermediate-high sea-level rise. Of greatest concern is the flood risk for homes initiating a 30-year mortgage in the year 2020. Between the years 2020-2050, homes that were inundated by Hurricane Ike are 64% likely to observe another Ike-level flood, while homes that were raised to the 11-foot Base Flood Elevation (BFE) have an 83% chance of storm tide inundation within a 30-year mortgage. In addition to numerous graphics in this paper, we created an interactive web-tool that enables users to select various flood events and time intervals to obtain estimates of future flood inundation at the property level.

I. Introduction

I. a. Background

The city of Galveston was established in 1839 and grew quickly as a prosperous port. By the end of the 19th Century, Galveston's population grew to 37,000 residents, as the port became one of the wealthiest cities per capita in the U.S. (McComb 1986).

A category-4 hurricane pushed a massive storm surge into the city on September 8, 1900, killing 6,000-8,000 people in the city and as many as 12,000 people when including the surrounding area (McComb 1986), making it the deadliest natural disaster in U.S. history (Emanuel 2005).

The city responded with fierce determination, and within a decade of the 1900 Storm, Galveston was protected by a 17-foot seawall and massive grade-raising project that elevated more than 500 city blocks. The value of these projects quickly became evident, as Galveston fared better during hurricanes that struck in 1909 and 1915.

Galveston has always benefitted from its prosperous port, however, through the 20th and 21st century, Galveston has reinvented itself as a hub for tourism, popular destination for retirement and a location where two universities, University of Texas Medical Branch (UTMB) and Texas A&M Galveston, conduct cutting-edge research. Modern Galveston has also experienced a revival in historic renovations and Galveston Historical Foundation boasts one of the largest membership bases among historical foundations in the country.

However, despite recent decades of renewed prosperity, Galveston continues to remain vulnerable to flood hazards. The seawall provides direct protection from the Gulf, but large, slow-moving hurricanes displace substantial amounts of salt water into Galveston Bay and Galveston Harbor, flooding the city from the "back side".

The most recent example of a large storm surge flood occurred in 2008, when Hurricane Ike generated a 12-foot storm tide (storm surge + tide) (Federal Emergency Management Agency 2008) that inundated approximately 60% of the city.

Ike's impact remains fresh on the mind of most Galvestonians and provides motivation to make the island more resilient in the future. As the city continues to grow, insights into best practices for development and preservation in a hazardous setting become ever more important.

I. b. Non-standardized Building Elevations Create Challenge for Flood Risk Assessment

Risk assessment is a crucial early step towards preventing widespread flood losses. Such assessments involve detailed analysis of both flood climatology and human development.

Developing an inventory of flood risk for buildings in Galveston is challenging because thousands of buildings are raised to different heights above ground level. This complicates flood risk analysis because it forces us to know more than just the ground elevation of a property; we also must know how high the building on the property is elevated.

New construction along the coastline is required to be elevated to specific levels, which the Federal Emergency Management Agency (FEMA) calls Base Flood Elevation (BFE). However, in historic cities like Galveston, thousands of buildings existed before such regulations existed and were permitted to remain at lower levels, as they were "grandfathered in". For this reason, one notices many Galveston neighborhoods where homes are elevated to different levels above the ground.

While elevation certificates are required for some practices, such as new home construction, a comprehensive database of building elevations in the city does not yet exist. This means that even if we could accurately predict future flood levels, such forecasts would provide limited utility for understanding flood impacts because we cannot yet connect flood levels with a quantity of buildings flooded and the economic impact of flooding.

I. c. Project Funding

Mississippi-Alabama Sea Grant Consortium, in partnership with the Gulf of Mexico Alliance, funded Galveston Historical Foundation on a 10-month project to analyze the vulnerability of buildings to coastal flooding in Galveston, Texas. This project was funded as a $30,000 pilot project to develop useful flood risk analysis locally, while creating innovative methodologies that are transferrable to other regions.

This project endeavors to use cutting-edge technology to assess the risk of future floods in Galveston. We will develop a unique methodology that efficiently utilizes Google Earth and Google Street View to estimate First Floor Elevation (FFE) levels. These building levels will be analyzed against storm surge data and projected sea-levels to provide a unique assessment of flood risk and flood impacts in the city.

Galveston Historical Foundation is situated in a unique position to succeed at a project of this scale, as the organization has embarked upon a long-term effort to improve Galveston's resiliency to coastal hazards following Hurricane Ike (2008). These efforts have included creating the Center for Coastal Heritage and Resiliency, hosting Living on the Edge, a multi-disciplinary conference that brought national and international experts to Galveston, and the creation of resources to improve Galveston's resiliency.

The city of Galveston provides an ideal setting for this project as well, as it contains a dense quantity of historic buildings, yet functions as a modern-day city with thriving businesses and a massive medical center. The city's island location, bordered by Galveston Harbor, Galveston Bay and the Gulf of Mexico, make it vulnerable to flooding on all sides, forcing the city to face the coastal flooding threat head-on for the sake of survival.

I. d. Selecting a Project Area

We interacted closely with the City of Galveston's Planning and Development Division for guidance on choosing a 40-block area for this study. Catherine Gorman, the division's Assistant Director and Historic Preservation Officer, guided us to an area between Broadway and Seawall Boulevard, east of Rosenberg (25th St.). This area is ideal for the project because the City is in the process of improving information for this region. This area was also a transition zone of flooding during Hurricane Ike, as lower-elevation homes took in considerable storm surge flooding, while higher-elevation homes remained dry. These characteristics make the area ideal for researching the impacts of sea level rise on future flooding.

II. First Floor Elevation (FFE) Mapping Method

II. a. Preparing for Community Mapping

The first step in this project involved preparing for community mapping. We chose a 40-block area, bounded by 13th and 23rd Street (10 blocks long), Avenue K on the north and Avenue N in the south (4 blocks wide). Figures 1 and 2 provide maps of the project area.

Figure 1. Map of the Project Area on Galveston Island. This map shows the project area relative to downtown Galveston, the UTMB Medical Campus and the Seawall.

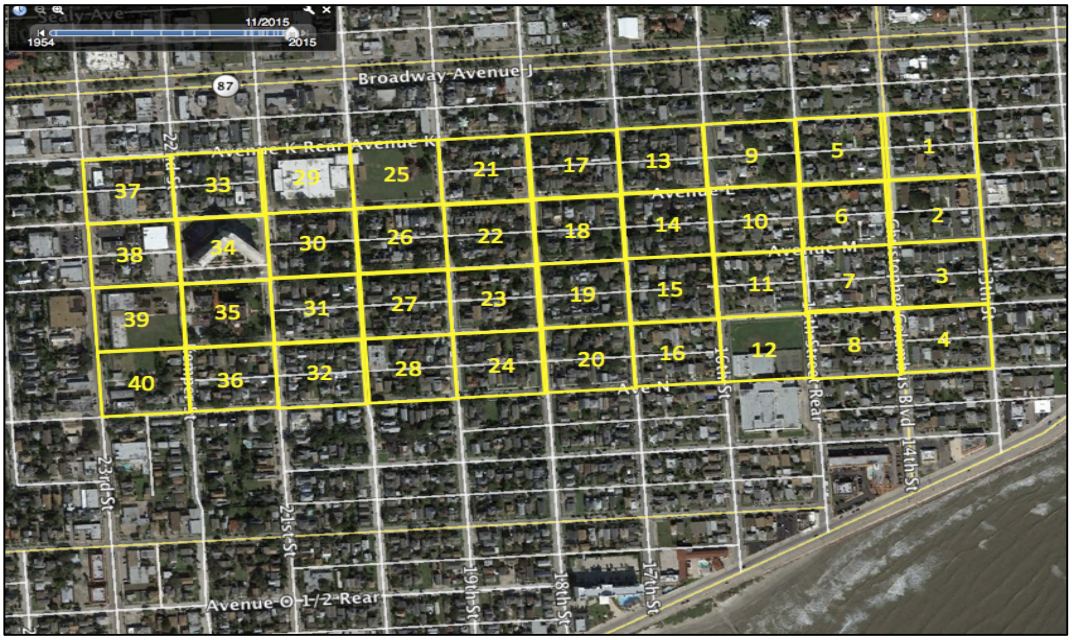

Figure 2. Zoom-in map of the 40-block area covered by this project. Each city block was given a unique ID number. Note the Gulf of Mexico in the lower-right portion of the map.

Galveston Island was intentionally raised during a massive grade raising project in the early 1900s. Locations closer to the Gulf of Mexico (south/ southeast) generally have higher ground elevations than locations near Galveston Harbor (north/ northwest). This pattern is descriptive of our study area, as ground elevations should typically be higher closer to the Gulf of Mexico, which is seen on the bottom-right portion of the map.

We created a zoomed-in map of each block to geographically display the unique ID numbers we assigned to each building. ID numbers identified the block number followed by a decimal point and the building number. For example, Building ID 7.04 matched with the fourth building in Block 7. The lowest ID numbers are assigned to the northwest corner of each block, with numbers increasing in a clockwise fashion. Figure 3 provides a map of Block 7 with unique building ID numbers.

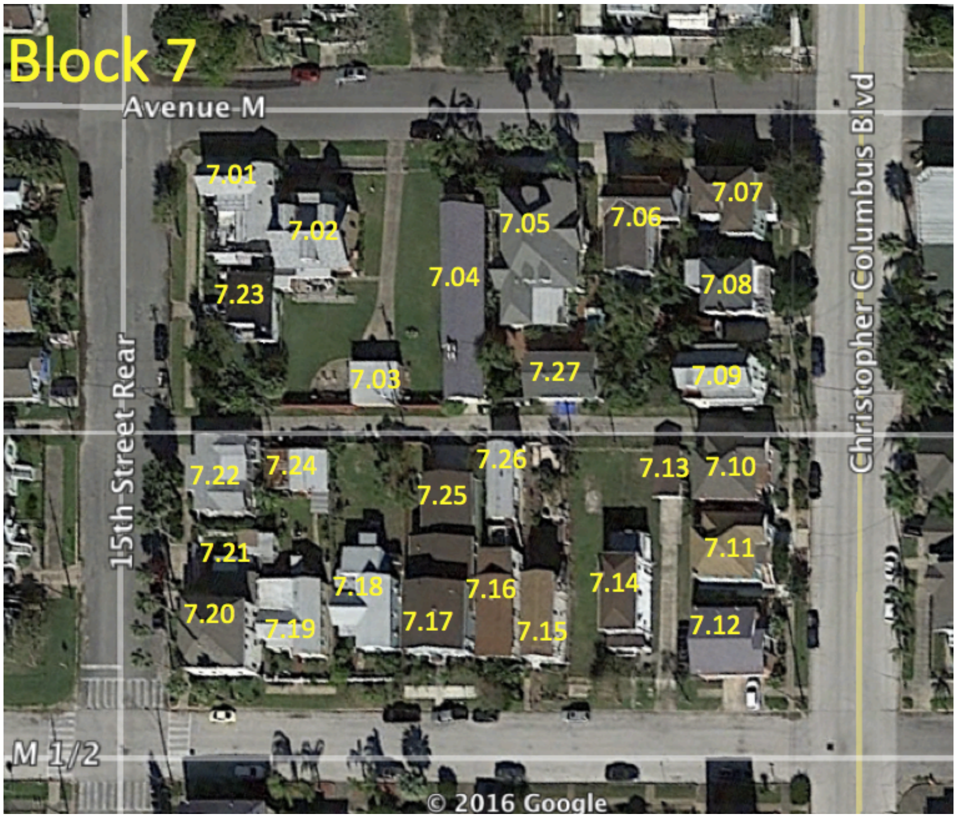

Figure 3. Map of Block 7 with unique building ID numbers. We created maps for 40 city blocks with unique building ID numbers.

Galveston contains many buildings with downstairs and upstairs addresses. In most cases, these buildings contain two different apartment units, however, some cases are mixed use, with commercial designation downstairs and residential upstairs. In these cases, both units share the same building ID and are designated by letters A and B, such as Building IDs 13.12A and 13.12B.

After labeling each building with an ID number along the four sides of the block, we labeled the buildings on the inside of the block as well, bordering the alley that was found in most blocks. Most of these buildings were sheds or garages.

The identification process provided a unique ID for 802 different buildings in our study area. Multiple units (upstairs and downstairs) were identified in 32 buildings, providing a total of 834 building units for analysis.

It should be noted that we use the term First Floor Elevation (FFE) as an estimate of the elevation of the first habitable floor. In cases with upstairs and downstairs units, we used this term for both units, even though the upstairs unit is located on the second habitable floor.

The average number of buildings per block was approximately 20, as 802 unique building IDs were mapped across 40 city blocks. However, most blocks contained more than 24 buildings.

Several blocks, like Block 25, which only contained one building, substantially reduced the average per block.

II. b. A Methodology for Estimating First Floor Elevations (FFE) above Ground Level

We developed an innovative method to use Google Earth and Google Street View to estimate First Floor Elevations (FFE) above Ground Level. The methodology uses Google Street View images to measure the vertical distance between the ground and a building's first floor. This distance, measured in pixels on a computer screen, is then converted to feet and inches to provide an estimate of the actual real-world elevation.

The method involves taking three measurements and performing simple math to convert computer pixels to feet and inches in the real world. We have listed below the three measurements that are required:

1. In Google Street View, measure the vertical distance, in computer pixels, from the ground to the first habitable floor;

2. In Google Street View, measure the horizontal distance, in computer pixels, of the roof line that is in the same plane as the measurement taken in Step 1;

3. In Google Earth, find the building on the satellite/ air photo imagery. Zoom in and measure the horizontal distance, in inches, of the roof line measured in Step 2.

This methodology works well because Google does not stretch Street View images along horizontal or vertical plane. This means that the ratio of pixels to inches for a vertical measurement, like the FFE, is identical to the ratio of pixels to inches for a horizontal measurement, like the roof line.

The key connection in this process is the roof line, because we obtain both the number of computer pixels and number of real-world inches for this line. These measurements enable us to calculate a pixel-to-inch ratio for the roof line, which can then be transferred to the FFE measurement if the roof line and FFE measurement are in the same plane.

Figures 4 and 5 provide screen shots of the measurements we took when looking at Google Street View and Google Earth satellite imagery. Both images are different perspectives of the same building.

Figure 4. *Screen shot of measurements taken from Google Street View images*.

Figure 5. *Screen shot of measurement taken from Google Earth satellite imagery*.

Appendix A provides a more detailed step-by-step procedure that walks us through the process. These steps can be used to estimate FFE for any building in any community if the building is found on Google Earth satellite imagery and is located on a street with Google Street View.

We also created an archive of marked-up images that provide guidance through our methodology. These images provide insights on the standard FFE approach (vertical FFE and horizontal rooflines both clearly visible), as well as more challenging situations that are less than ideal. This archive is found on the First Floor Elevation Mapping page on U-Surge. Link: https://www.u-surge.net/first-floor-elevation-mapping.html.

We found that although our methodology quickly provides accurate FFE estimates, the procedure is often more complicated than taking three measurements and creating a pixel-to-inch ratio. Obstructed Street View Images, roof lines in different planes, images taken at oblique angles and the use of stairs as a tool for estimating the ground line are all more complicated scenarios that challenge the person using this method.

III. Results

III. a. Analysis and Cancellations

This methodology was useful for estimating FFE levels for 479 out of 834 buildings (57.4%) in the project area. Unfortunately, we were unable to estimate for 355 buildings (42.6%).

The two main reasons for the inability to estimate FFE were as follows:

1) The building was obstructed by trees, shrubs, a fence or another object in 183 cases (51.5% of the cancelations);

2) The building was located along an alley or was otherwise not within the site of Google Street View in 147 cases (41.4% of the cancelations);

These two reasons accounted for 93% of the cancelations. The remaining 7% of cancelations occurred for a variety of reasons, such as inability to align the vertical and horizontal measurements in the same plane.

While a “success” rate of 57.4% FFE estimates in the region may seem low, we must keep in mind that the purpose of this project was to provide a community-wide flood risk assessment, rather than to analyze flood risk at one specific property. The nearly 500 buildings that provided useful data in this study gave us crucial data-driven assessment on flood risk.

It is important to note that most of the buildings canceled for reason #2 (located along alleys) were garages and sheds. These type of “out-buildings” are typically not elevated but flood impacts on these buildings affect households less severely than flood impacts in habitable houses and commercial operations.

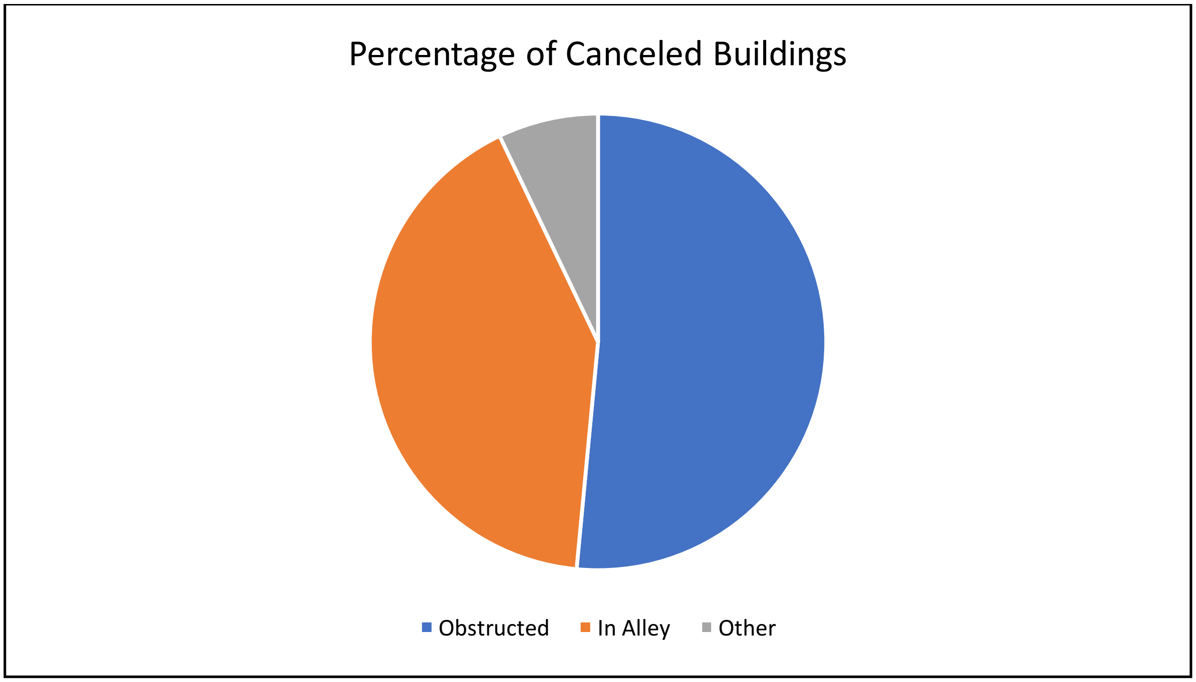

Figure 6. Pie chart depicting the reason for canceling a building record and not obtaining a FFE estimate.

III. b. Break down of Building Characteristics

The majority of the buildings analyzed in this study were residential (90.8%). The next highest categories were garages (3.8%) and commercial (2.9%). Table 1 provides the number and percentage of buildings in each category. Figure 7 provides a pie chart depicting the percentage breakdown.

Category	Number of Buildings	Percentage of Total Buildings
Residential	435	90.8
Garage	18	3.8
Commercial	14	2.9
School	7	1.5
Religious	4	0.8
Shed	1	0.2
Total	479	100.00

Table 1. A breakdown of the types of buildings analyzed in this project.

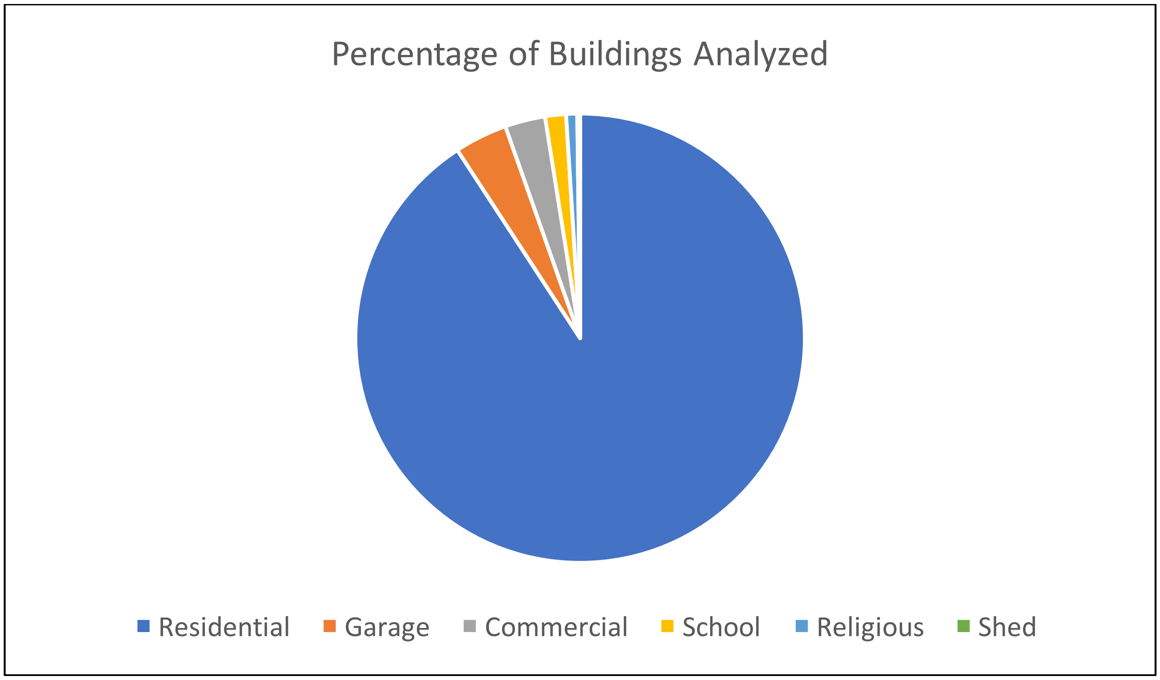

Figure 7. A visual breakdown of the types of buildings analyzed in this project. The majority were residential.

Of the 479 buildings analyzed in this study, 429 buildings (89.6%) were elevated above the ground and 50 buildings (10.4%) were situated directly at ground level, which is sometimes referred to as "slab-on-grade" construction type. All garages in this study area were non-elevated, accounting for 18 (36%) of non-elevated buildings. However, the largest group of non-elevated buildings were residential, as 24 (48%) of the non-elevated buildings were classified in this group. Other non-elevated buildings included commercial and religious buildings, a school and a backyard shed.

III. c. Time Requirements

As the methodology for FFE mapping became more efficient and repetitive, less time was required to map each city block. This time eventually minimized to approximately four hours per city block. However, it should be noted that several major steps were required before we could obtain these efficient results.

For example, the rate of one block per four hours occurred only after we mapped the entire project area, created a zoom-in map of each block, and identified/ mapped the unique ID for each building in the project. This was a time-intensive approach that required us to map a unique ID for more than 20 different buildings in most city blocks.

Another important perspective is that the 3-step methodology we developed took considerable time to refine. Early in the project we used a less efficient procedure that required the operator to use different Google Street View scenes to make additional measurements. This early methodology required a measurement to be made from the target (building) to the path line of the Google Vehicle in the street, which was usually mapped. This procedure was both less efficient and less accurate than our final method.

Finally, the 4-hour time estimate for mapping a city block did not include field work (see section below). Taking 22 field measurements took longer than expected because we wanted to obtain permission before making measurements and most of our buildings were residential. Considerable time was often required to find homeowners, as people were often at work during the day and unavailable when we came for field work. Other buildings were second (vacation) homes that were unoccupied during field work days.

Eventually, we got permission for each measurement, but the time to travel to the field sites, interact with people and take the measurements should be considered if budgeting time and/or money to utilize this methodology for future projects.

III. d. Field Observations

Field measurements of first floor elevations above ground level were an important component of this project because they verified the accuracy of our methodology. We measured 22 field observations over the study area. These observations were scattered geographically, to ensure that we were field testing a variety of different neighborhoods and development types. Field observations were taken in 14 different city blocks.

Figure 8 depicts a map of the field work locations. The map shows the locations of 21 sites (not 22), because we measured the FFE of both downstairs and upstairs units in the same building in Block 13. Red circles depict all field site locations on the map in Figure 8.

Figure 8. Map of the 21 sites of our field observations, depicted by red circles. These observations verified the accuracy of our virtual methodology. We took 22 observations at these 21 sites.

The distribution of observations is slightly higher in the eastern half of the study area because this area contains a higher density of raised buildings. The western half of the study area contains more large buildings, like schools and residential facilities, as well as more businesses, which often tend to have low first floor elevations or slab-on-grade profiles, where the building rests directly on the ground.

Field observations were taken with a tape measure on buildings in which property owners were present and gave permission for a measurement to be taken. An unexpected benefit of this procedure is that it gave us an opportunity to engage with residents and explain the project. All residents gave permission to take a measurement and most were interested to learn more about the project.

III. e. Statistical Analysis of Methodology

Figure 9 provides a linear regression of estimated and actual first floor elevations. This analysis shows a significant correlation between the two variables, exceeding the 95% confidence level, as the R^2 value of this analysis 0.9825.

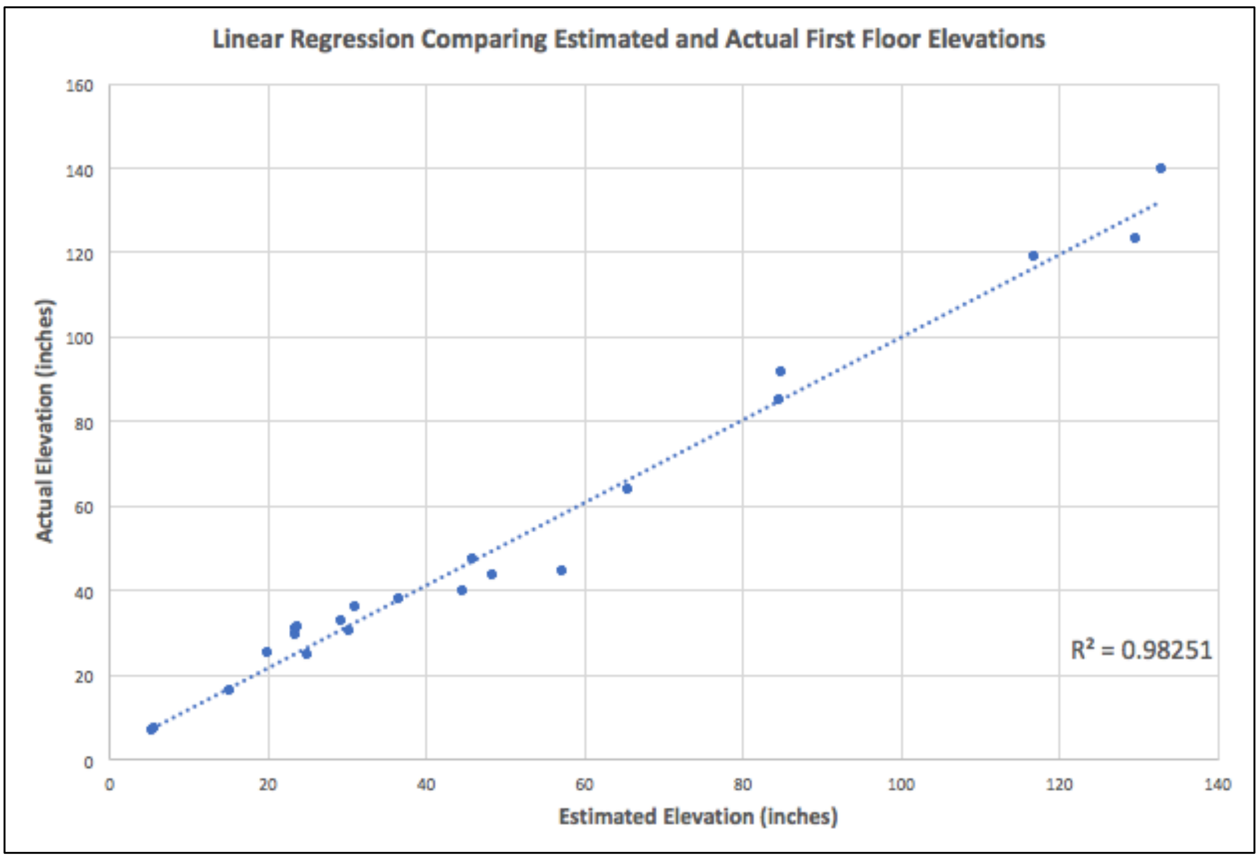

Figure 9. Linear regression comparing estimated and actual inches of first floor elevation above ground level. The R^2 value is 0.9825.

At our field sites, the average estimation error was 3.93 inches, with a maximum error of 12.95 inches and a minimum error of 0.23 inches. These results were obtained when taking the absolute value of error measurements, as some errors underestimated and others overestimated actual elevations. When absolute values are not considered and over- and under-estimates average each other out, the cumulative average error of measurement was (-0.95 inches). This means that over 22 field samples, our methodology had a bias that underestimated actual first floor elevations by slightly less than 1 inch, on average.

The average first floor elevation above ground level for these 22 field samples was 50.13 inches, so a cumulative underestimation less than 1 inch reveals a sample-wide bias that underestimates actual elevations by less than 2% of their actual value. These results reveal that although the methodology in this study does not perfectly estimate first floor elevations, it does provide an accurate approach for estimating first floor elevations across an urban landscape.

III. f. Break Down of First Floor Elevations (FFE) above Ground Level

For the entire study area, FFE above ground level varied considerably, with the highest value reaching 13.6 feet and the lowest value equaling 0 feet, shared by 50 different building units that were classified as slab-on-grade. The average building was raised 4.63 feet, when including the non-elevated buildings, and 5.17 feet when not including non-elevated buildings in the average.

III. g. Adding Ground Elevations

We obtained surface elevation data through the United States Geological Survey (USGS) viewer for The National Map (https://viewer.nationalmap.gov/basic). This source provides elevation data that are valid for the year 2014.

The digital elevation model (DEM) has a horizontal resolution of 1/3 arc-second – roughly 98 feet (30 meters) – and is referenced to NAVD88. We extracted surface elevation by querying the DEM grid cell nearest to a point of interest using several open-source Python libraries (GDAL, shapely, NumPy, pandas, GeoPandas).

We matched these raster (gridded) elevation data to specific properties to estimate the ground elevation beneath buildings. Ground elevations above NAVD88 for each of these buildings ranged from 8.31 - 11.96 feet, with an average value of 9.38 feet.

Combining FFE above ground level and ground level above NAVD88 provided a total FFE above NAVD88. These values ranged from 8.38 - 22.59, with a mean value of 14.01 feet. These values are depicted on the scatter plot in Figure 10.

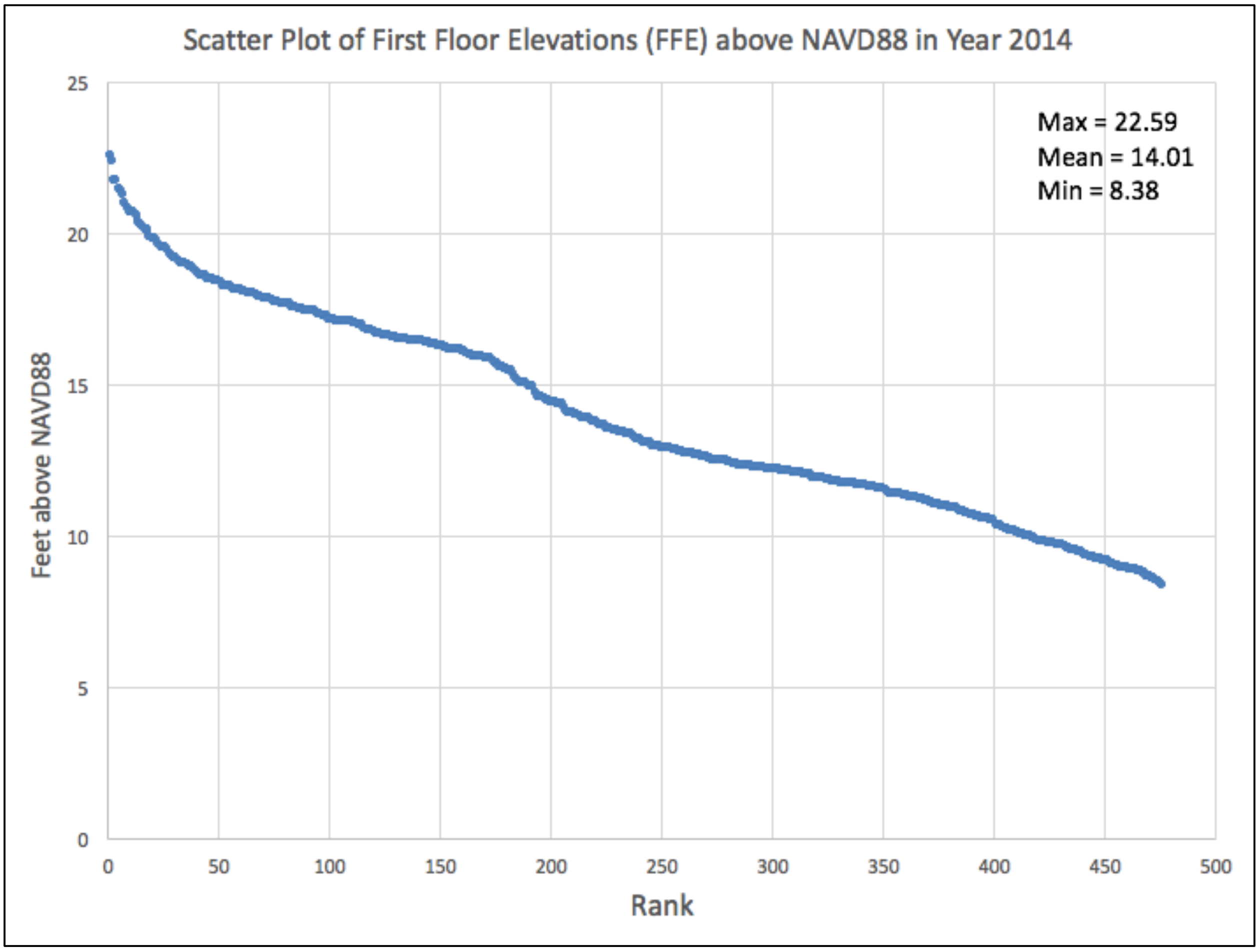

Figure 10. Scatter plot of First Floor Elevations (FFE) above NAVD88 datum. These elevations are valid for the year 2014.

IV. Storm Surge Data and Statistics

IV. a. Data Selection

Throughout Galveston's history, hurricane-generated storm surges have inflicted the most severe floods in terms of both water levels and impacts. Torrential rain from both tropical and non-tropical weather systems generate more frequent inundations than storm surge, but the magnitude and impact of rainfall-induced flooding is considerably less than storm surge flooding. Therefore, this project will analyze only storm surge frequencies and magnitudes and disregard heavy rainfall events.

During this project, Hurricane Harvey produced minor flooding in Galveston but catastrophic damage just north of the city and throughout much of the Houston Metro area. Galveston Scholes Airport received approximately 22.84" of rain from the multi-day event, but areas less than 35 miles north of Galveston received more than 50" of rain (National Weather Service 2017).

Harvey's flooding throughout hundreds of miles of Southeast Texas revealed the complexity of a widespread catastrophic rain event, as this storm flooded neighborhoods in different ways. Some neighborhoods flooded from local torrential rain that could not drain quickly enough. Others experienced riverine flooding from rivers, creeks and bayous that swelled to many times their original size and engulfed entire communities. Some neighborhoods in west Houston flooded from the intentional decision to open Barker and Addicks Reservoirs to prevent the possibility of catastrophic dam failure.

As Galveston is a sloped island with no rivers or proximity to flood-control reservoirs, flooding in the city was limited to heavy rainfall flooding that overwhelmed local drainage. Many streets were inundated, and flood waters entered vehicles on these streets and the buildings in the most flood-prone areas. The worst flooding occurred downtown, but as much as two feet of water inundated neighborhoods south of Broadway, including streets in our study area. Nonetheless, flood impacts in our study area were mostly confined to street flooding and impacts on buildings were minimal.

We must note that while Harvey inflicted the worst rainfall-induced floods on record in the region, numerous storm surge events have produced more severe flooding in Galveston. Essentially, Harvey confirmed that Galveston's greatest flood vulnerability is to saltwater flooding from combined storm surge and sea-level rise and reassured us in our decision to focus this analysis on saltwater flooding.

IV. b. Expanding U-Surge

The U-Surge Project (www.u-surge.net) provides a platform for developing the first coastal flood climatology for U.S. cities. This project had previously provided a historical storm surge database for Galveston, however, the record was incomplete. We completed this database and made it useful for statistical analysis to better understand the risk of extreme water levels at Galveston.

The first step involved going through raw tide gauge records to pull out storm tide (storm surge + tide) levels for numerous hurricanes and tropical storms. U-Surge previously provided data for substantial storm surge events, however, the record was incomplete for low-magnitude storm surges, which could only be obtained from the raw tide gauge records. Although low-magnitude surges, ranging from 1-4 feet, do not cause substantial damage, a complete dataset of these events is crucial for accurately calculating storm surge statistics.

We obtained all tide gauge records within a circle with a 10-mile radius, centered on Galveston. Figure 11 provides a map of the data-selection area. This methodology follows Needham (2014), which found data-selection circles of this size maximize the amount of data, while keeping the dataset homogenous.

Figure 11. Map of Galveston's 10-mile data-selection circle.

We identified three tide gauges with available data within this data-selection circle. All three gauges are listed on the NOAA Tides and Currents website, and are listed as follows:

Tide Gauge #1
Galveston Pleasure Pier

This tide gauge is located on the Gulf side of Galveston Island, just off the seawall at 25th Street. It provides hourly water levels since 1957, however, some periods are missing data. Most notably, no data are provided from March 1981 – May 1991, and the record stops on July 20, 2011. The complete record of data availability is posted on Galveston's U-Surge site.

Tide Gauge #2
Galveston Pier 21

This tide gauge is located along Galveston Harbor, on the "harbor" or "bay" side of the island. The popular Pier 21 restaurant/ commercial area along the harborside is named after this location. The Pier 21 tide gauge provides the longest record of any tide gauge along the U.S. Gulf Coast, with hourly data beginning in 1904. Several short periods are missing data and the complete list of data availability is listed on Galveston's U-Surge site.

Tide Gauge #3
Galveston North Jetty

Galveston's North Jetty tide gauge is located along a jetty consisting of a wall and large rocks, extending off the southwest corner of Bolivar Peninsula. This location represents water levels near the mouth of Galveston Bay. It contains the shortest record length of the three tide gauges, with hourly and 6-minute observations beginning in 2001. Hurricane Ike destroyed the gauge, making it inoperable from 2008-2011. Data are available from April 11, 2011 to present.

IV. c. Constructing a Comprehensive Record of Storm Tide Events at Galveston

We analyzed high water marks from each tide gauge for all hurricanes and tropical storms that passed within 200 miles of Galveston. After obtaining these data, we selected the highest credible water mark for each event. The highest credible water mark sometimes came from tide gauge data, but other times came from sources like scientific reports or FEMA field work. Multiple observations were available for many hurricanes and tropical storms.

For example, we identified nine high watermarks for Hurricane Ike, but selected the 12-ft water level provided by FEMA as the highest credible water mark for Galveston's storm surge record. Table 2 provides a list of these nine observations, which were provided from FEMA, USGS, the National Hurricane Center and NOAA Tides and Currents.

This effort was time-intensive, as dozens of hurricanes and tropical storms have impacted Galveston since the 1800s. However, this step proved to be beneficial, as we identified 15 high watermarks that were not previously listed in Galveston's U-Surge database, and verified that we selected the most credible high watermark for all events.

Location	Lat	Lon	Surge	Storm Tide	Datum	Obs Type	Source
Unlisted	29.2952	-94.9168		11.90	NAVD88	Coastal Stillwater	FEMA
Unlisted	29.3003	-94.9152		11.80	NAVD88	Coastal Stillwater	FEMA
Unlisted	29.2445	-94.8743		10.50	NAVD88	Coastal Stillwater	FEMA
Unlisted	29.3073	-94.7941		12.00	NAVD88	Coastal Stillwater	FEMA
Pleasure Pier	29.2850	-94.7883		11.04	NAVD88	NOS Tide Gauge	NOAA Tides and Currents
Galv Bay Entrance	29.36	-94.72	9.41	9.75	MLLW	NOS Tide Gauge	Nat'l Hurricane Ctr
Pier 21	29.2790	-94.8010	10.05	10.82	MLLW	NOS Tide Gauge	Nat'l Hurricane Ctr
Bolivar Peninsula	29.3500	-94.7230	9.84		NORMAL ASTRO TIDE	High Water Mark	USGS
Eagle Point	29.3650	-94.7060	11.48	11.95	MLLW	NOS Tide Gauge	Nat'l Hurricane Ctr

Table 2. High water marks from Hurricane Ike (2008) that were observed within 10 miles of Galveston, Texas. We selected the highest water level for each event- in this case a 12-ft storm tide provided by FEMA.

IV. d. Converting Storm Tide Data to a Common Datum

After compiling a comprehensive list of storm tide events for Galveston, we converted these water levels to a common datum, or vertical reference line, for statistical analysis. This step was like converting temperature records in Fahrenheit and Celsius into one common scale for consistency.

We chose to convert the data to North American Vertical Datum of 1988 (NAVD88), as this datum has become the standard reference for FEMA's Flood Insurance Rate Maps (FIRM). We determined to use datum conversions from Pier 21, as this site provides the longest record of the three tide gauges.

Fortunately, NOAA Tides and Currents provides a datum conversion table and graphic that provide the water level of NAVD88 compared to various tidal datums, like Mean Low Water (MLW), Mean Sea Level (MSL) and Mean Higher High Water (MHHW). Figure 12 depicts these water levels in a graphic.

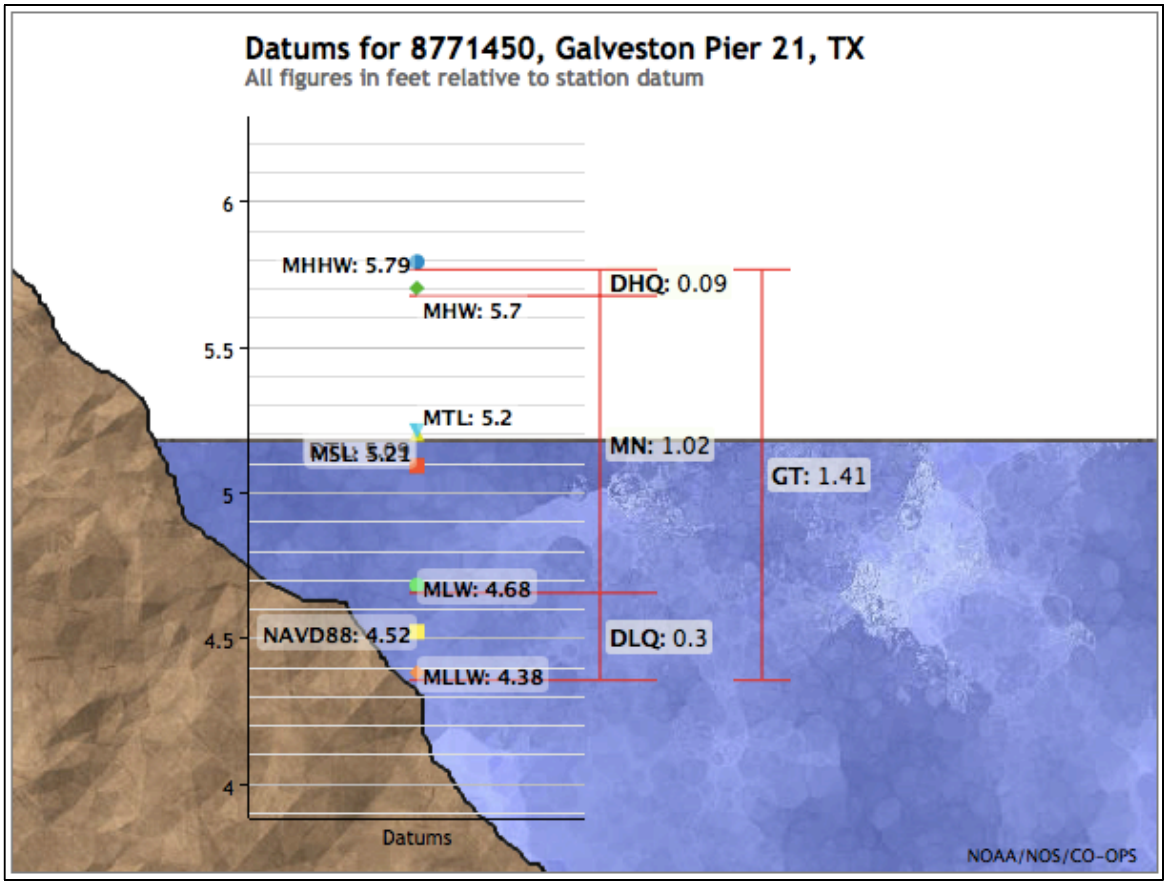

Figure 12. Graphic of datum levels at Pier 21 provided by NOAA Tides and Currents. NAVD88 stands for the North American Vertical Datum of 1988, and represents the datum to which we convert all water levels.

As sea levels along the Upper Texas Coast are rapidly rising relative to the ground level, it was important to identify the year these datum conversions were established. This is important because tidal datums, like MLW, MSL and MHHW, are increasing over time, while NAVD88 is based on the surface of an ellipsoid, which remains unchanged over time.

NOAA Tides and Currents lists the "Tidal Datum Analysis Period" for Pier 21 as January 1, 1997 – December 31, 2001. This 5-year analysis period has a mean year of 1999, so we selected that year as our time stamp for datum conversions. In other words, we considered the various water levels depicted in Figure 9 to represent an accurate picture of datum conversions in the year 1999.

These datum conversions are linear, meaning we simply add or subtract water levels when converting from one datum to another. For example, in 1999, the level of MSL was 0.69 feet higher than NAVD88. Therefore, when converting from MSL to NAVD88 we added 0.69 feet to the water level, making a storm tide of 3 feet above MSL equal to a storm tide of 3.69 feet above NAVD88.

These datums are classified in the Present Epoch, and were accepted into use on April 17, 2003 (NOAA Tides and Currents 2017). Any observations recorded after this date were already in the

Present Epoch and simply needed to be converted from a tidal datum to NAVD88, if the original observation was not already listed in NAVD88.

Another period, called the Superseded Epoch, was established using data from 1990-1994 and has a mean year of 1992. We used these datums for all surge events between November 4, 1999 (the date this epoch was accepted) and April 17, 2003 (the date the Present Epoch was accepted).

Prior to 1999, NOAA Tides and Currents is unclear about epoch references for Galveston Pier 21. For example, a high watermark from 1942 may be listed as 5.2 feet above MLW datum, but we do not have a specific Epoch to use for conversion from MLW to NAVD88.

In these cases, we assumed that all observations before 1999 were measured over an "annual datum", following logic introduced by Needham (2014). Therefore, a high watermark measured above MLW in 1942 is assumed to observe a high watermark above Mean Lower Water (MLW) for the year 1942.

Tidal datums are assumed to be stationary over time, meaning the difference between MLW and MSL in 1942 is considered to be identical to the difference between those datums in 1999.

However, sea levels are not stationary over time. To convert the 5.2 ft MLW observation from 1942 into a level above NAVD88, we first converted MLW (1942) to MLW (1999), then made the conversion from MLW (1999) to NAVD88 (established in Galveston using mean data from 1999).

We used NOAA's Sea Level Trends data to make this conversion. The data on NOAA's website shows that relative sea level rise along the Upper Texas Coast is rising rapidly, as this region and South Louisiana are experiencing the fastest levels of relative sea level rise in the nation (National Oceanic and Atmospheric Administration 2017).

Figure 13 provides a long-term linear sea level rise rate of 6.47 mm/ year, which converts to 2.12 ft/ century, or 0.0212 ft/ year (National Oceanic and Atmospheric Administration 2013). We used this trend to convert water levels from the year of observation to 1999, and then used the datum conversions previously listed to convert tidal datums to NAVD88. Using this procedure we could convert all observed high watermarks to water levels above NAVD88.

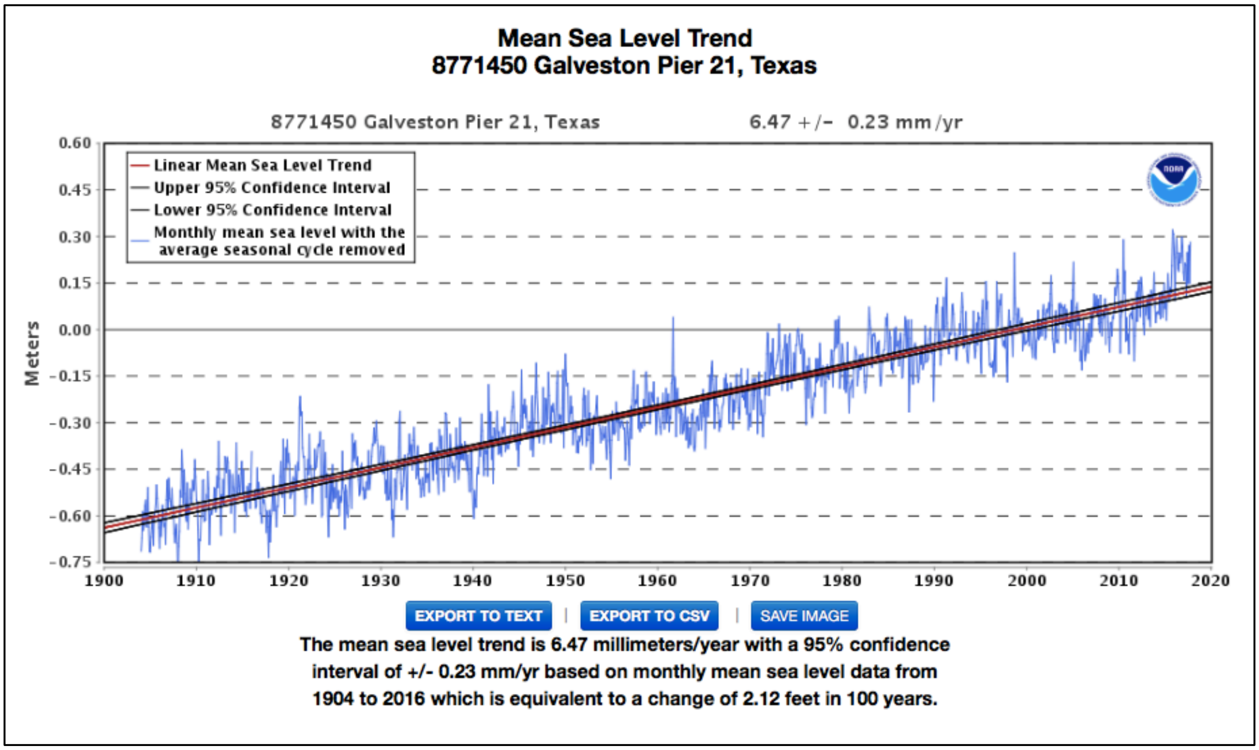

Figure 13. Graph of water levels at Galveston Pier 21 provides a sea-level rise rate equivalent to 2.12 ft in 100 years, or 0.0212 ft per year. Source: NOAA Tides and Currents.

IV. e. Creating a Time Series of Galveston's Storm Tide History

This methodology provided us with a comprehensive dataset of storm tide levels above NAVD88 datum for 94 hurricanes and tropical storms since 1880. Figure 14 depicts a time series of these high watermarks. We added a blue, triangular polygon to depict the height of Mean Sea Level above NAVD88 for each year since 1900. We calculated this level based on datum conversions for the Present Epoch, provided by NOAA Tides and Currents, which listed MSL at 0.69 ft above NAVD88 in 1999. We used the long-term linear sea level rise trends to estimate MSL for each year in the graphic.

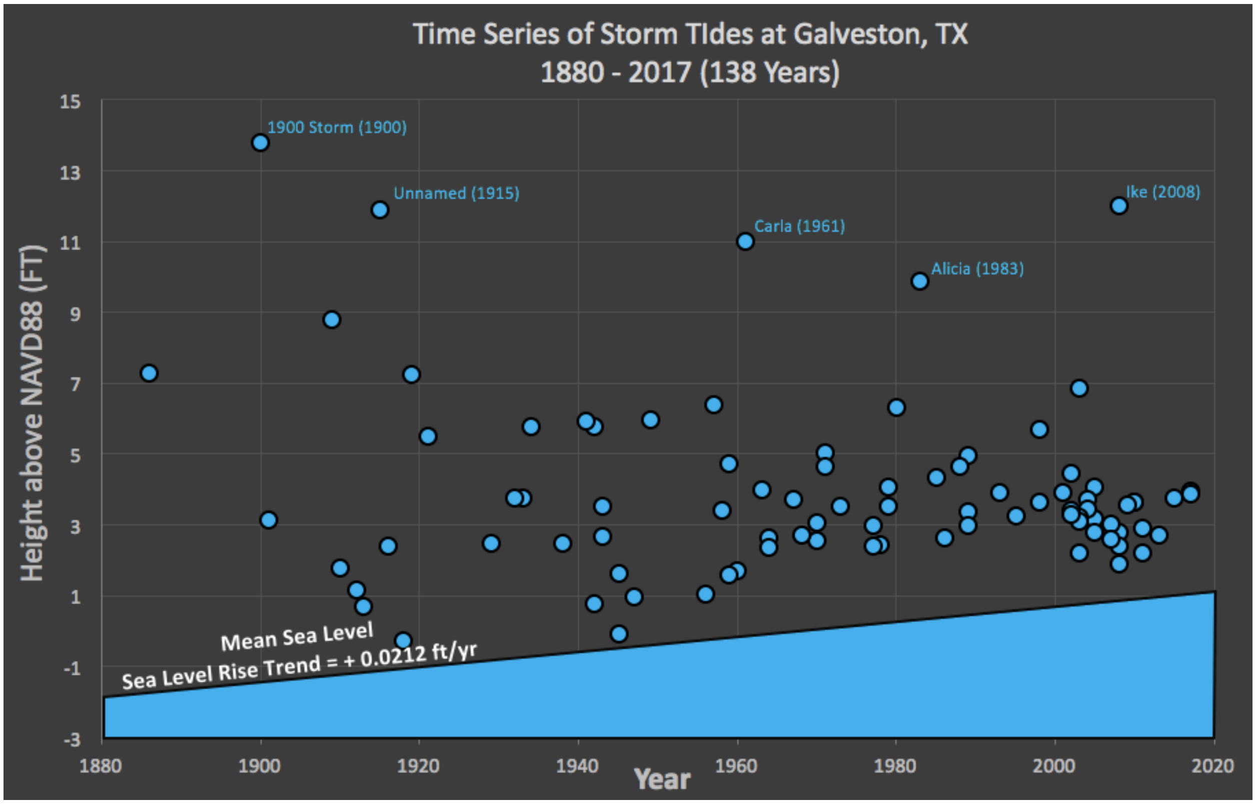

Figure 14. Time series of mean sea level and the maximum storm tide from 94 hurricanes and tropical storms in Galveston since 1880.

IV. f. Building a Histogram of Galveston's Storm Tide History

Although the time series graphic provides a rich history of coastal flood history at Galveston, the data behind this graphic are not useful for analyzing extreme water levels because they contain water displaced by both storms and sea-level rise. Statistics of extreme events assume stationarity of the dataset, so it became necessary to detrend these data and remove the influence of rising seas.

This step gives heavier weight to older storms, which displaced more water than modern storms that observe total storm tides at the same level. For example, if storms in 1910 and 2010 both generated storm tides that reached 6 feet above NAVD88, we intuitively conclude that the storm in 1910 displaced more water because sea levels in 1910 were lower than 2010. The long-term rate of 2.12 feet of sea-level rise per century tells us that the storm in 1910 would need to displace 2.12 feet of additional water to reach the same storm tide level as the storm in 2010.

This step involved calculating the difference between the year of the storm and the year 1999, when the datums were established for the Present Epoch. We added 0.0212 ft for every year before 1999 and subtracted the same amount for every year after 1999.

Once the contribution for sea-level rise was removed, we obtained a clearer picture about the amount of water displaced per storm. For example, hurricanes Carla (1961) and Ike (2008) both displaced the same amount of water- as storm tide levels reached 11.12 feet above Mean Sea Level for their respective years. However, in the 47 years between those storms, sea levels in Galveston rose precisely one foot, enabling Ike's storm tide to reach 12 ft above NAVD88, compared to Carla, which only reached 11 ft above NAVD88.

A histogram of these data depicts the storm tide height for 93 hurricanes and tropical storms since 1900 (Figure 15). These events are ranked from highest (left) to lowest (right), regardless of their year of occurrence. Water levels are plotted above Mean Sea Level for their respective years.

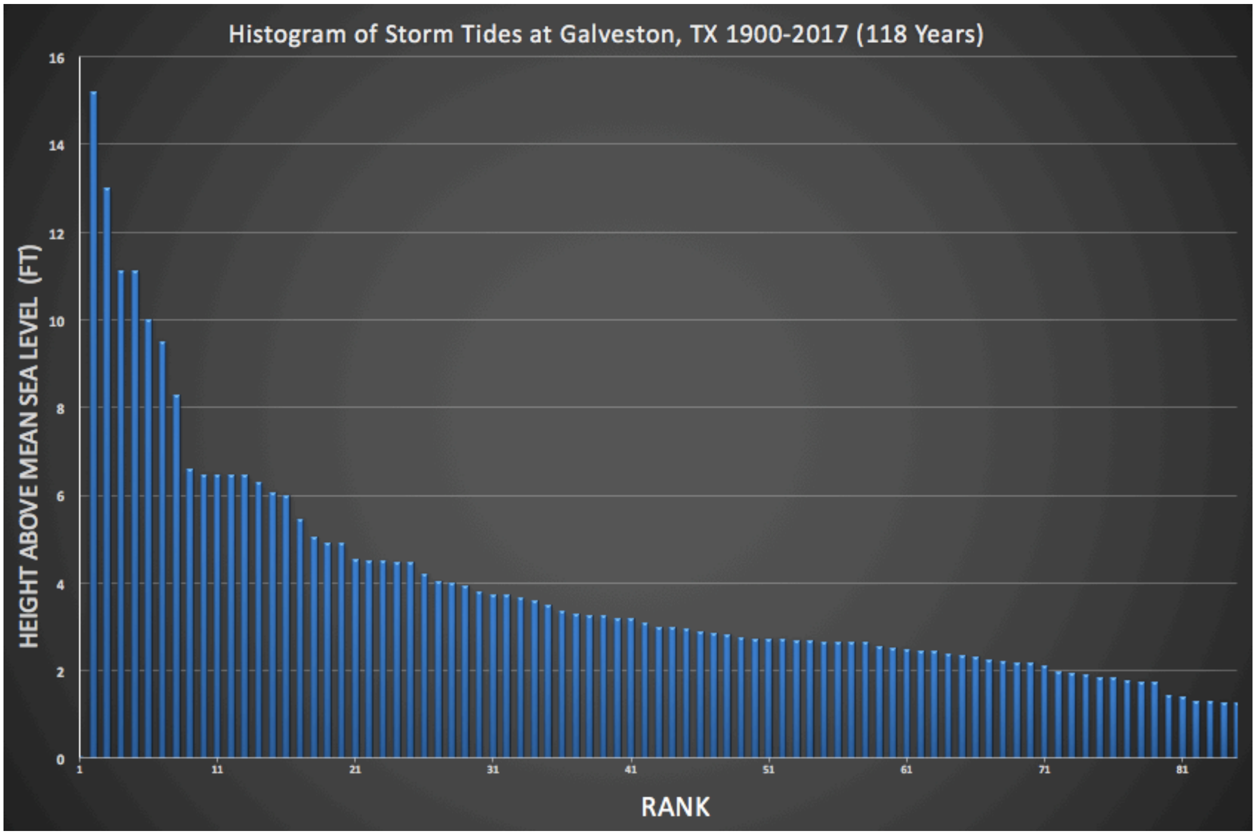

Figure 15. Histogram of high water marks from 93 hurricanes and tropical storms between 1900-present at Galveston. These water levels have removed the influence of sea level rise to give us the best estimate of how much water each storm was displacing above Mean Sea Level for the year of the storm.

Table 3 provides a list of the top 5 detrended water levels. The 1900 Storm generated the highest water level over both "annual MSL datum" and NAVD88. The unnamed hurricane of 1915 generated the second highest water level above "annual datum", but Hurricane Ike (2008), generated the second highest water level above NAVD88, taking advantage of 93 years of sea level rise to reach a higher total water level than the 1915 hurricane.

A simplified way to think of the difference between "annual MSL datum" and NAVD88 is to think of data measured above the annual datum as the amount water pushed by each storm, with sea level rise removed, but NAVD88 to represent the water level that we would see if we looked at a high watermark on a post, which includes water from both the storm and sea level rise.

Storm Name	Year	Water Level above "Annual MSL Datum"	Water Level above NAVD88
1900 Storm	1900	15.19	13.78
Unnamed 1915	1915	13.00	11.91
Carla	1961	11.12	11
Ike	2008	11.12	12
Velasco	1909	10	8.79

Table 3. List of top 5 storm tides measured over "annual MSL datum" and NAVD88. Although Ike's water level ties it for third place over annual MSL datum, it reached the second highest water level over NAVD88 because of many decades of sea level rise following Hurricane Carla.

IV. g. Extreme Water Level Statistics

We used the data behind the histogram, storm tide magnitudes over "annual MSL datum" with detrended sea-level rise, to calculate return periods of extreme water levels. Following standard practices, we calculated the return period for the 500-, 200-, 100-, 50-, 25- and 10-year storm tide events. These are water levels we expect to be reached or exceeded, on average, once during the period.

Following Needham (2014), we used logarithmic plots, which is a form of the Gumbel Distribution. At 26 sites along the Gulf Coast, from Texas to Maine, Needham (2014) found this method to provide the optimal statistical results when compared to Extreme Value Theory, a branch of statistics designed to estimate extremes beyond the record length of data.

Such plots have been used widely in previous studies (Huff and Angel 1992; Faires et al. 1997; Sindhu and Unnikrishnan 2012).

Huff and Angel (1992), and Faiers et al. (1997) have produced such plots by incorporating the Weibull plotting position formula:

Exceedence Probability = Rank / (n+1)

where "n" is the number of years in the data record. Makkonen (2008) provides a detailed discussion of plotting position formulas and their limitations in engineering design. Exceedence probabilities were then utilized to calculate return periods in years, utilizing the formula:

Return Period = 1 / Exceedence Probability

The Huff-Angel linear regression technique, used by Huff and Angel (1992), utilizes a log-log scale (for the x and y axes), thereby graphing and linearizing the surge events in their appropriate Weibull plotting position. Faiers et al. (1997) also utilized a linear regression procedure, with a log scale on the x-axis (return period), and a linear scale on the y-axis (event magnitude). We determined to use the log-linear method employed by Faires et al. (1997) after visually assessing the fit provided by both methods.

Although we have identified high watermarks as early as 1837 in Galveston, we selected the time-period 1900-2017 for this analysis, to maximize the number of years in the data record, while minimizing missing data. Storm tide data from prior to 1900 are scarce in Galveston, a common occurrence for coastal cities.

Figure 16 shows the log-linear regression for statistical analysis of extreme water levels. Blue diamonds represent observed water levels, while the black regression line provides a best fit to the data. The R^2 value of this regression is 0.97, meaning the data correlate significantly at greater than the 95% confidence level.

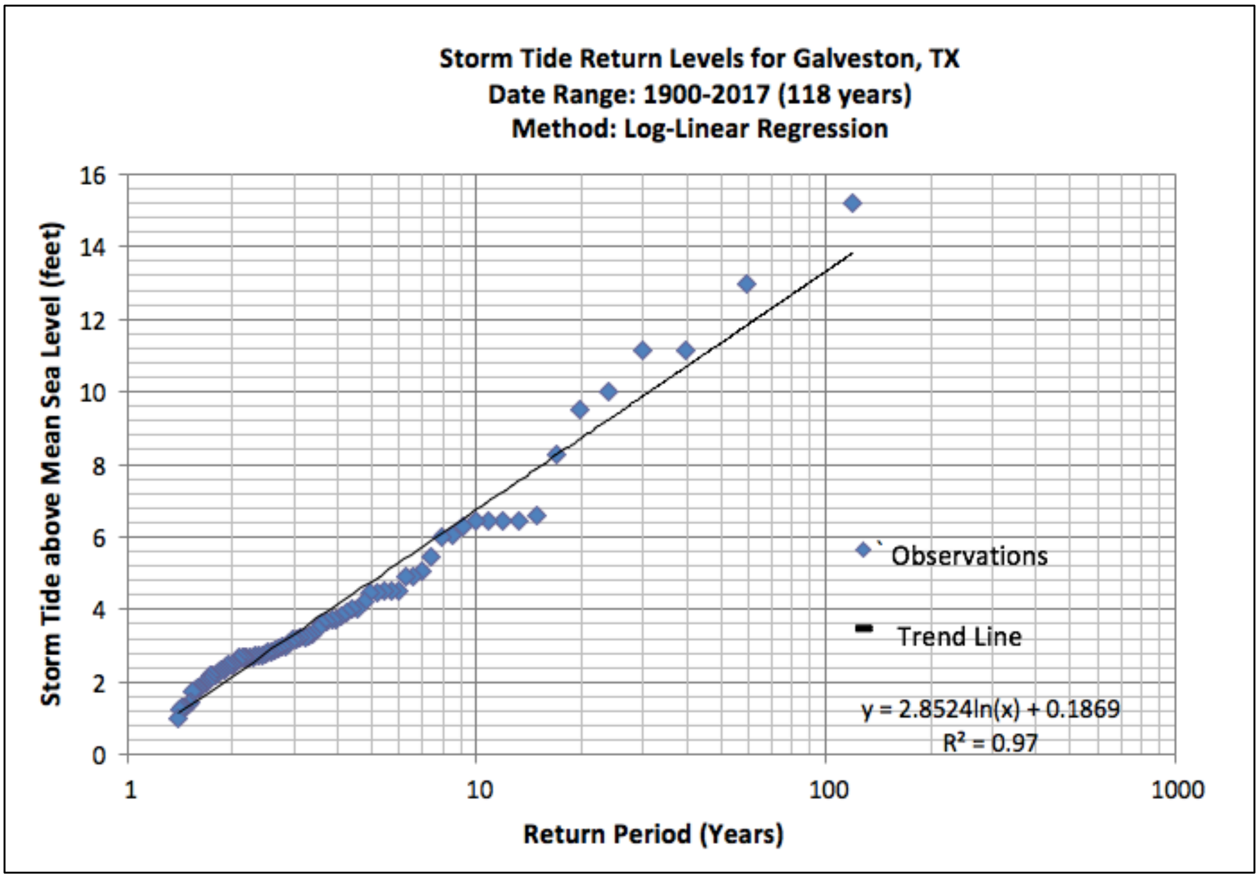

Figure 16. Log-linear regression of extreme water levels in Galveston from 1900-2017. Blue diamonds depict actual observations, while the black regression line plots the best fit.

Table 4 provides the water levels for various return periods. The 100-year storm tide in Galveston is listed at 13.34 feet, while the 10-year event reaches 6.75 feet. We provided levels for the 500- and 200-year events, although this method is not designed to analyze data beyond the period of record.

We can use the equation on the graph in Figure 16 to estimate the return period of high-profile hurricane storm tides, listed in Table 3. According to the regression equation, the 1900 Storm generated a 193-year flood and hurricanes Carla (1961) and Ike (2008) both generated 46-year floods. This means that Ike and Carla generated flood levels (above Mean Sea Level for their years) that should be reached or exceeded only once every 46 years, on average.

Return Period	Storm Tide* (Feet above Mean Sea Level)
500-year	17.52
200-year	15.30
100-year	13.34
50-year	11.34
25-year	9.37
10-year	6.75

Table 4. Water levels associated with selected return periods at Galveston.

V. Sea Level Rise

V. a. Choosing Sea Level Rise Scenarios

We used long-term linear sea-level rise rates in our procedure to convert all historic high watermarks to the same datum. The sea-level rise rates were needed to convert water levels from numerous storm events to their equivalent heights in 1999, and then convert from tidal datums to NAVD88.

However, sea-level rise rates are also important as we consider future flood risk in coastal cities like Galveston. Numerous scientific sources provide sea-level rise scenarios based on model runs of future atmospheric conditions, such as the level of carbon dioxide in the atmosphere.

Galveston observes a rapid rate of sea-level rise from a combination of eustatic (global) sea level trends and local subsidence, or sinking, of land. Over the past century, the contribution from subsidence was greater than the contribution from eustatic sea-level rise, meaning most of Galveston's rising sea level was due to the land sinking rather than the water rising.

However, most projections show eustatic sea level rise accelerating through this century, enabling the component from eustatic sea level rise to equal or exceed the contribution from subsidence on Galveston Island.

We referenced sea-level rise scenarios provided by the U.S. Army Corps of Engineers (2017) web-tool. This web-tool enables users to choose locations and various sea-level rise scenarios projected by different research groups.

Within the web-tool, we selected sea-level rise projections that come from National Oceanic and Atmospheric Administration (2017). We chose these projections because they are the most up-to-date projections provided and NOAA has an excellent international reputation as an authority on data and forecasts related to earth and ocean sciences. In addition, this project is funded through NOAA Sea Grant, so using NOAA's sea-level rise projections enables our study to provide outcomes that are consistent with other NOAA studies.

Using data provided for Galveston's Pier 21, we obtained projected sea levels that extend to the year 2200 for seven carbon dioxide emission scenarios: linear, low, intermediate-low, intermediate, intermediate-high, high and extreme. These levels are depicted in Table 5 and Figure 17.

These sea-level rise rates are considerably higher than projections released in the first decade of this century. The disintegration of the Larsen B ice shelf in 2002 and the widespread melt season in Greenland in 2012 are two examples of unpredicted, high-profile changes near the poles that suggest ice sheets are melting quicker than previously projected (Goodell 2017). Recent research indicates that melting of Antarctic ice could alone contribute 3.3ft (1m) of sea-level rise by the year 2100 (DeConto and Pollard 2016).

Galveston Pier 21
Scenarios for GALVESTON I
NOAA2017 VLM: 0.01522 feet/yr
All values are expressed in feet

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.15	0.26	0.30	0.36	0.46	0.52	0.52
2020	0.30	0.52	0.59	0.72	0.85	0.95	0.98
2030	0.46	0.82	0.92	1.15	1.35	1.57	1.71
2040	0.61	1.12	1.25	1.57	1.90	2.26	2.53
2050	0.76	1.38	1.54	2.03	2.56	3.12	3.54
2060	0.91	1.67	1.87	2.59	3.31	4.17	4.82
2070	1.07	1.90	2.17	3.15	4.17	5.31	6.17
2080	1.22	2.17	2.49	3.77	5.12	6.59	7.78
2090	1.37	2.43	2.82	4.43	6.17	8.07	9.61
2100	1.52	2.62	3.05	5.09	7.28	9.61	11.58
2120	1.83	3.12	3.71	6.17	9.12	12.76	15.98
2150	2.28	3.74	4.59	8.30	12.96	18.93	23.98
2200	3.04	4.72	6.00	12.27	20.70	31.46	39.30

Table 5. Projected water levels at Galveston Pier 21 from years 2000 to 2200 given various sea-level rise scenarios. Data provided by National Oceanic and Atmospheric Administration (2017).

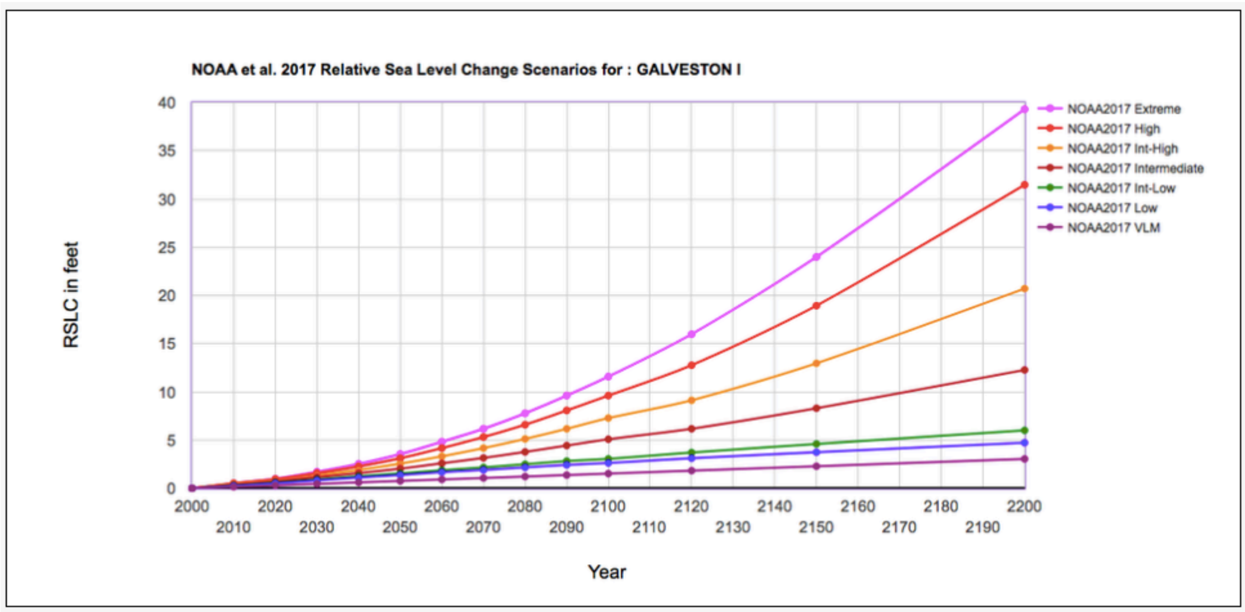

Figure 17. Graphical display of projected water levels at Galveston Pier 21 from years 2000 to 2200 given various sea-level rise scenarios. Data provided by National Oceanic and Atmospheric Administration (2017).

V. b. Determining Baseline Flood Levels for the Year 2000

We determined a baseline flood risk by estimating extreme water levels in the year 2000. Mean Sea Level was established at 0.69 ft above NAVD88 in 1999, the year datums were established at Galveston Pier 21. Given a long-term sea-level rise trend of 0.0212 feet per year, we estimated that MSL in the year 2000 was 0.71 feet above NAVD88.

V. c. Adding Sea Level Rise to Baseline Flood Levels

We added sea-level rise to the baseline flood levels to estimate flood levels for the years 2020, 2050 and 2100. In this step, we used intermediate and intermediate-high sea-level rise projections from Table 5.

For example, the 100-year storm tide level of 13.34 feet was added to a MSL of 0.71 ft in 2000, to obtain a combined 100-year water level of 14.05 feet above NAVD88. By the year 2050, the intermediate sea-level rise projection raises the 100-year water level to 16.08 feet, while the intermediate-high sea-level rise projection raises the same event to 16.61 feet. Tables 6 and 7 provide water levels for various extreme events in the years 2000, 2020, 2050 and 2100.

These analyses make use of an approach that hydrologists often refer to as a “bath tub” model. The “bath tub” analogy refers to a water level in a container increasing as water is added to it, much the way water in a bathtub rises as we add water from a faucet or bucket.

This approach does not account for complex interactions related with fluid dynamics, coastal erosion or other dynamic changes along the coastline that may occur in coming decades. It does not predict varying rates of water flow across the landscape. It also does not account for future civil engineering projects, flood defenses and/or changes to development and local drainage that may impact future flooding. Rather, the "bath tub" model focuses on estimating vertical water levels by adding the various water sources (storm tide, sea level rise, etc).

Event	2000	2020	2050	2100
500-year flood	18.23	18.95	20.26	23.32
200-year flood	16.01	16.73	18.04	21.10
100-year flood	14.05	14.77	16.08	19.14
50-year flood	12.05	12.77	14.08	17.14
25-year flood	10.08	10.8	12.11	15.17
10-year flood	7.46	8.18	9.49	12.55
1900 Storm	15.9	16.62	17.93	20.99
Hurricane Ike	11.83	12.55	13.86	16.92

Table 6. Combined water level from Extreme Event Level + Mean Sea Level (MSL) adjustment + sea level rise for the years 2000, 2020, 2050 and 2100 with intermediate sea-level rise projection.

Event	2000	2020	2050	2100
500-year flood	18.23	19.08	20.79	25.51
200-year flood	16.01	16.86	18.57	23.29
100-year flood	14.05	14.9	16.61	21.33
50-year flood	12.05	12.9	14.61	19.33
25-year flood	10.08	10.93	12.64	17.36
10-year flood	7.46	8.31	10.02	14.74
1900 Storm	15.9	16.75	18.46	23.18
Hurricane Ike	11.83	12.68	14.39	19.11

Table 7. Combined water level from Extreme Event Level + Mean Sea Level (MSL) adjustment + sea level rise for the years 2000, 2020, 2050 and 2100 with intermediate-high sea-level rise.

VI. Flood Risk Analysis

We superimposed combined water levels (Tables 6-7) on the scatterplot of FFEs (Figure 10) to calculate the number of buildings that would be inundated for each flood scenario. However, before we could conduct this analysis, we needed to make a small adjustment on the FFE data.

The water level datums were established in the year 1999, however, ground elevations were measured for the year 2014. This is a problem because ground levels in Galveston were subsiding between the years 1999 and 2014. This subsidence is built into the sea-level rise projections, but it is also measured in the 2014 ground level elevations. So essentially, these 15 years of subsidence are counted twice.

To adjust for this error, we needed to remove these years of subsidence to estimate ground levels in the year 1999, when the datums were established. We estimated long-term subsidence rates by comparing local sea-level rise trends to eustatic (global) rates, and attributing the difference to subsidence.

The Intergovernmental Panel on Climate Change (IPCC) estimated an average global sea-level rise rate of 0.07 inches per year, or approximately 7 inches per century, between the years 1961-2003 (IPCC 2007; Needham et al. 2012). However, the long-term sea-level rise trend in Galveston is 2.12 feet/ century (National Oceanic and Atmospheric Administration 2013).

The difference in these values, approximately 1.54 feet/ century, can be attributed to local subsidence. Estimating an annual rate of 0.0154 feet/ year, we calculated subsidence levels of 0.23 feet in the 15-year period from 1999-2014. We added this value, which is approximately 2.8 inches, to the ground level beneath each building in our study area. Although this was a minor adjustment, a difference in elevation of a few inches changes the wet/dry classification of dozens of buildings in our study area.

Once this adjustment was made we could superimpose water levels on an adjusted scatterplot of first-floor building elevations to determine the percentage of buildings that would flood during different magnitude floods in the years 2000, 2020, 2050 and 2100. Figure 18 shows a graphical example of flood impacts from the 25-year water levels subject to intermediate-high sea-level rise.

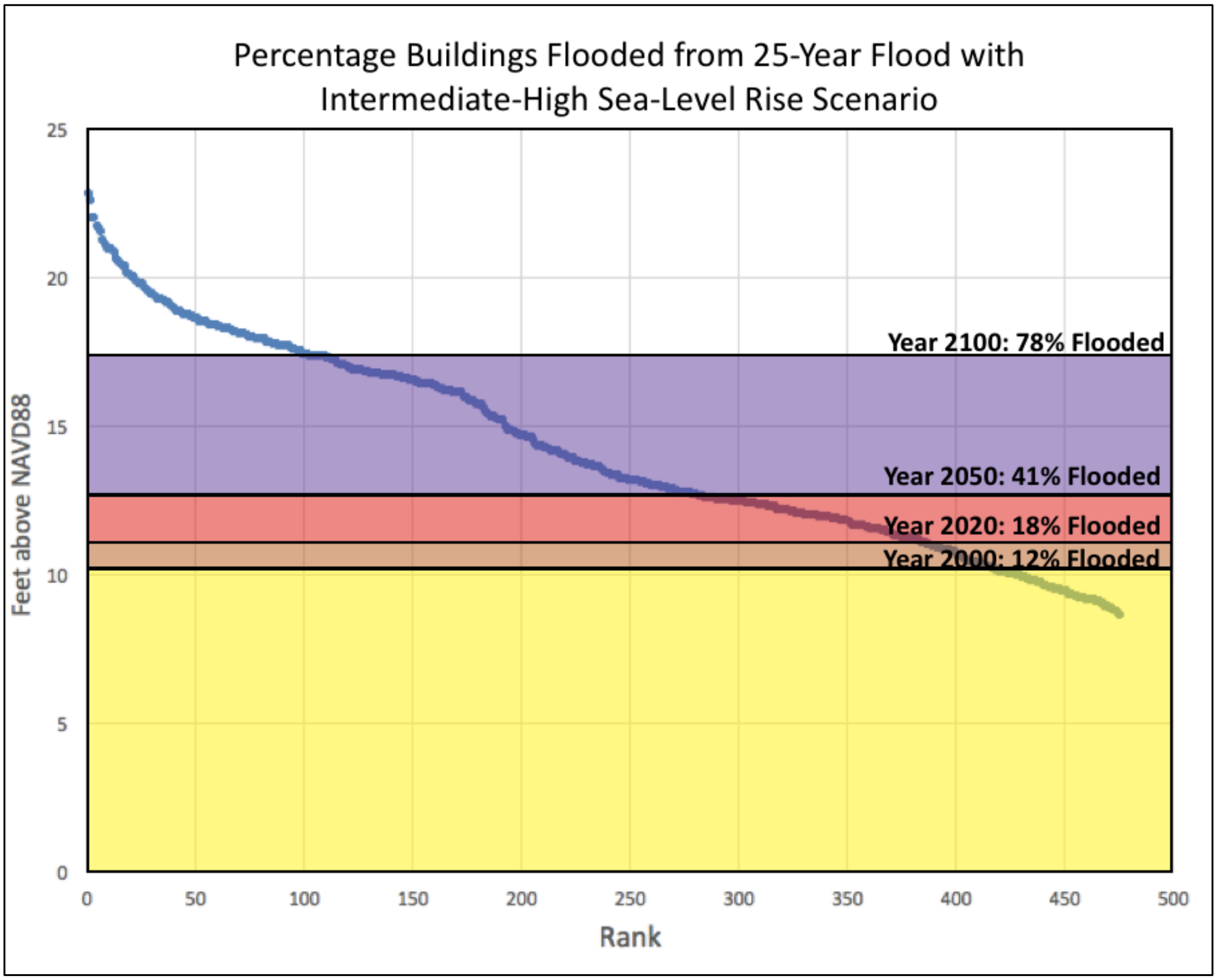

Figure 18. Percentage buildings flooded from 25-year flood with intermediate-high sea-level rise scenario.

After we superimposed water levels on first floor elevation scatterplots, we tabulated the total number and percentage of buildings flooded for intermediate and intermediate-high sea-level rise scenarios. Tables 8 and 9 provide numeric values of the percentage of buildings flooded, while Figures 19 and 20 graphically depict these values.

Event	2000	2020	2050	2100
500-year flood	86	92	96	100
200-year flood	64	71	84	98
100-year flood	54	59	64	92
50-year flood	31	43	54	76
25-year flood	12	17	32	60
10-year flood	0	0	6	39
1900 Storm	63	70	84	98
Hurricane Ike	27	39	53	74

Table 8. Percentage buildings flooded in 2000, 2020, 2050 and 2100 from combining extreme water levels and the intermediate sea-level rise scenario from National Oceanic and Atmospheric Administration (2017).

Event	2000	2020	2050	2100
500-year flood	86	92	97	100
200-year flood	64	74	89	100
100-year flood	54	59	70	99
50-year flood	31	44	57	93
25-year flood	12	18	41	78
10-year flood	0	0	11	59
1900 Storm	63	72	88	100
Hurricane Ike	27	41	57	92

Table 9. Percentage buildings flooded in 2000, 2020, 2050 and 2100 from combining extreme water levels and the intermediate-high sea-level rise scenario from National Oceanic and Atmospheric Administration (2017).

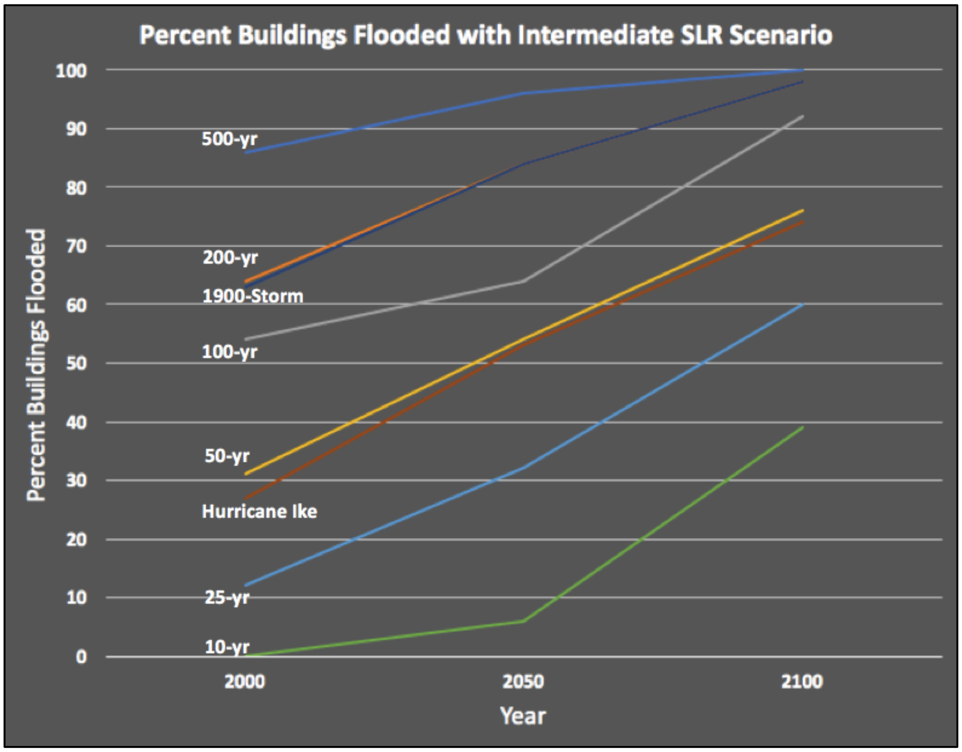

Figure 19. Percentage buildings flooded in present and future with intermediate sea-level rise scenario.

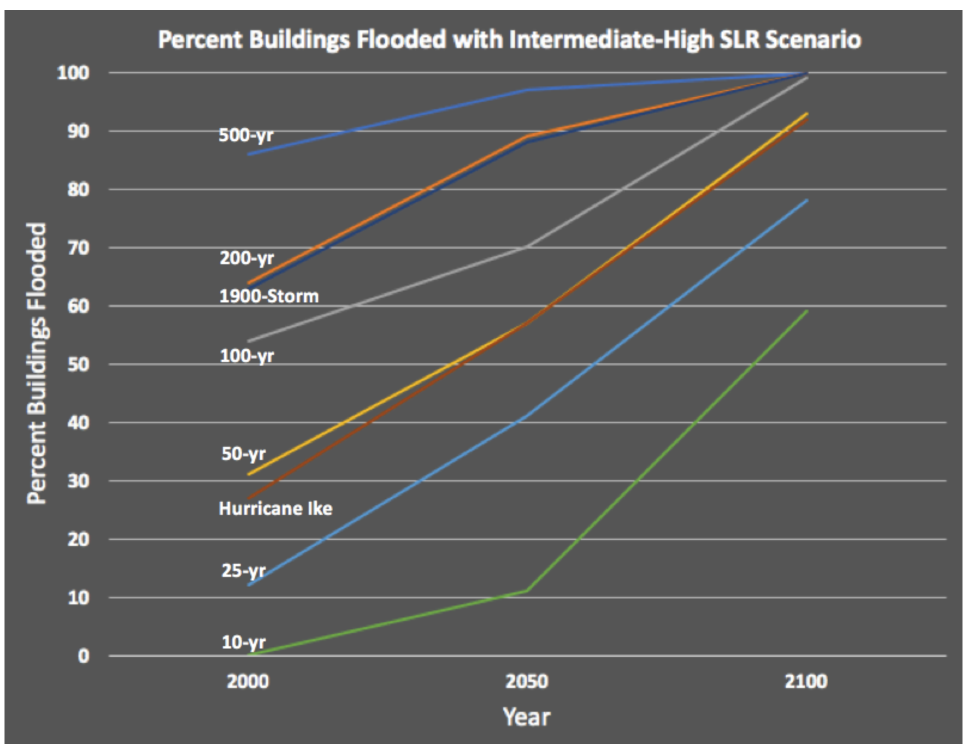

Figure 20. Percentage buildings flooded at present and in future with intermediate-high sea-level scenario.

VII. Flood Risk Discussion
Figures 18 and 19 depict a substantial increase in number of buildings flooded over time for storms of different frequencies. Several patterns stand out for storms of different magnitudes.

High-magnitude, less frequent storms, like the 500-year and 200-year storms, as well as the 1900 Storm, show a more rapid increase in number of buildings flooded between years 2000-2050 than from years 2050-2100. The graphs for these storms resemble log curves plotting building inundation into the future. This pattern is prevalent for these massive flood events because they begin to approach 100% inundation in the second half of the century. For example, with intermediate-high sea-level rise, the 500-year and 200-year storms have inundated 97% and 88% percent of buildings, respectively, by the year 2050, leaving little room to increase the number of buildings flooded in the second half of the century.

On the other hand, the 10-year storm, which represents the lowest-magnitude and highest frequency, depicts a slight rise in buildings inundated between 2000-2050, but a rapid rise of inundation during the second half of the century. The percentage of buildings flooded only increases from 0-11% from 2000-2050, but accelerates from 11%-59% from 2050-2100, with intermediate-high sea-level rise. This pattern makes sense when we consider that the 10-year flood is not high enough to inundate any buildings given the current sea-levels, but will rapidly overtake many buildings during the second half of this century.

Tables 8 and 9 are useful for estimating the number of buildings flooded during the upcoming 30-year mortgage cycle, as they provide estimates of inundation in the years 2020 and 2050. The greatest acceleration in number of buildings flooded during this period occurs from the 25-year flood, which increases 23% during this period, from 18% in 2020 to 41% in 2050. This pattern should concern us because homes are likely to observe a 25-year flood within a 30-year mortgage cycle.

VIII. Online Flood Mapping Tool

We created a mapping tool that enables users to visualize the extent of flooding based on the flood type, flood event and year of occurrence. This tool maps out flood inundation in specific buildings for various years and different sea-level rise scenarios. The following sections describe how we built this tool and how the tool can be utilized.

VII. a. Building the Online Mapping Tool

We obtained surface elevation data through the United States Geological Survey (USGS) viewer for The National Map (https://viewer.nationalmap.gov/basic). The digital elevation model (DEM) has a horizontal resolution of 1/3 arc-second – roughly 98 feet (30 meters) – and is referenced to NAVD88. We extracted surface elevation by querying the DEM grid cell nearest to a point of interest using several open-source Python libraries (GDAL, shapely, NumPy, pandas, GeoPandas).

We analyzed a range of flooding scenarios due to storm surge, taking into account the type of flooding, storm event, year and projections for sea level rise (SLR). Communicating the results in an accessible manner required us to break the problem down into a few essential components. We first combined the FFE, NOAA SLR and U-Surge datasets to enable spatiotemporal exploration of flood scenarios. The flood depth for a given scenario provided the basis for a set of simple filters:

DEM – surface elevation from USGS
FFE – first floor elevation calculated using field measurements and *DEM*
floodLevel – flood level for a combination of storm event, year and sea level rise
i,j,k – indices for filtered data points

Surface and First Floor Depth

$$surface_i = \{floodLevel - d_i \mid d_i \in DEM,\ d_i \leq floodLevel\}$$
$$firstfloor_j = \{floodLevel - f_j \mid f_j \in FFE,\ f_j \leq floodLevel\}$$

None

$$none_k = \{0 \mid n_k \in DEM,\ n_k > floodLevel\}$$

We generated a total of 144 filtered datasets with georeferenced flood depth information. Our client application is built as a static site; all code runs directly in the web browser and the server is only used to transfer datasets in JavaScript Object Notation (JSON) format. We use the open-source Leaflet library (leafletjs.com) for essential mapping functionality and the p5.js library (p5js.org) for enhanced visual and interactive elements.

VII. b. Using the Online Mapping Tool

The map tool provides interactive maps found at the following link: https://seagrant.tailwindlabs.io/. This site is designed to be user friendly, as people with limited technological background should find the interface intuitive.

In the upper right corner of this map, pull-down menus enable users to select settings. The pull-down menus on this page are “Flooding”, “Storm”, “Year”, and “SLR” (sea-level rise).

“Flooding” refers to the object over which flood levels are measured. Within this menu, “Buildings” measure flood depth above first-floor elevations of buildings, “surface” depicts flood levels above the ground and “none” depicts which properties remain dry.

For “Storm”, users may choose from the 500-, 200-, 100-, 50-, 25-, or 10-year flood events, as well as the 1900 Storm and Hurricane Ike.

For “Year”, users may choose 2000, 2020, 2050 or 2100. We selected the year 2000 because it is the year from which the sea-level rise scenarios begin and it represents approximate water levels in the decade before Hurricane Ike (2008). The year 2020 approximates the current flood risk for Galveston, 2050 represents mid-century flood risk and 2100 represents end-of-century risk, which many reports use as a benchmark for future flood projections.

For “SLR”, we loaded intermediate and intermediate-high scenarios. If users are interested in other sea-level rise scenarios, we could add that functionality in the future.

Once users select their settings, the map will display flood levels through the study area. Users can “mouse over” buildings and properties to see projected flood levels at these locations.

An icon and text in the bottom right of the screen provide summary statistics for the various maps. For example, summary statistics in the lower-right portion of the map show us that the 100-year flood will inundate 64% of the buildings in the study area, considering intermediate sea-level rise.

Figure 21 depicts a sample map. Note that flood waters are projected to inundate a building on Avenue M, between 17th and 18th St. with 2.0 feet of water in this scenario (see pop-up window near the middle of Figure 21).

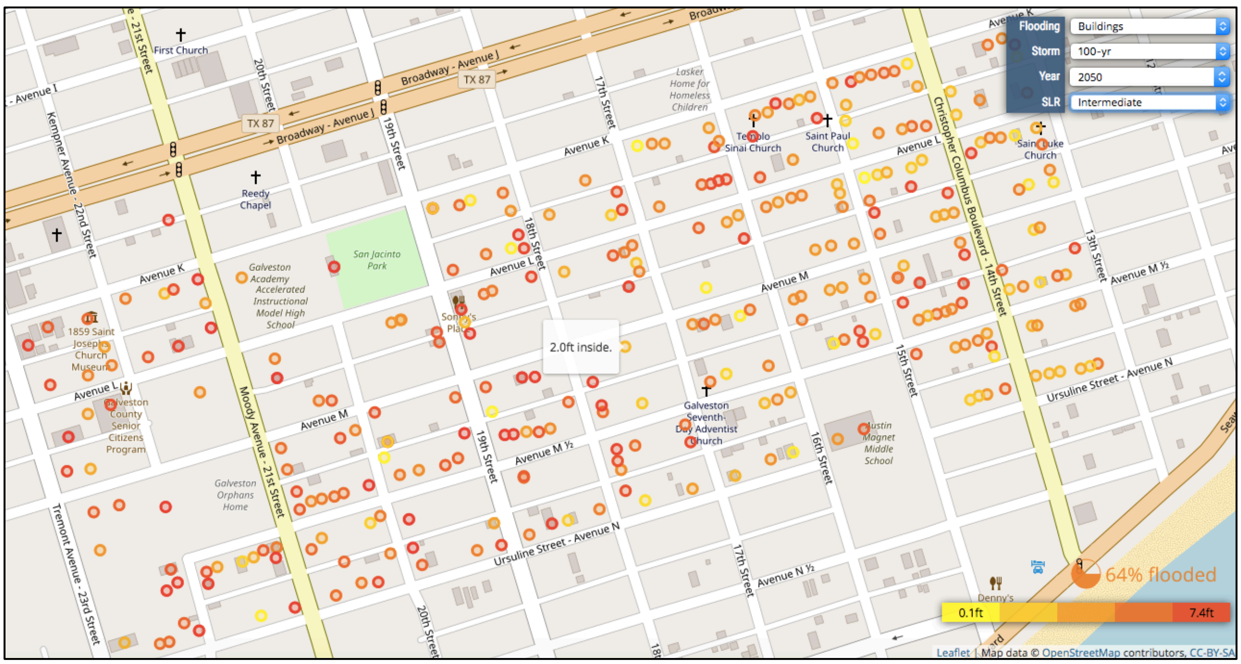

Figure 21. A map of flood risk from the 100-year flood in the year 2050 with intermediate sea-level rise. Summary statistics on the bottom right of map indicate that 64% of buildings in the project area will be flooded.

A few patterns stand out as users interact with this online map. If users select “surface” under the “flooding” tab they will see how much water is projected to inundate the ground level at each property. Flood depths generally increase as users approach the top and/or left of the mapping area and decrease near the bottom right area. This makes sense, as the seawall represents the highest ground and the bottom right area is closest to the seawall.

The pattern for inundation inside buildings resembles the pattern for surface (ground) flooding, but is not as strong. This pattern fits what we should expect, as buildings in the bottom right of the map are located on higher ground, but individual building elevations may more than offset the difference in ground elevation. In other words, a slab-on-grade construction style closer to the seawall may be more vulnerable to flooding than a building elevated 10 feet above the ground near the top of the map, where surface elevations are lower.

VIII. b. Considering These Findings in Context of a 30-Year Mortgage

Hurricane Ike generated an 11.12-ft storm tide above Mean Sea Level for its year of occurrence (2008). This is a 46-year event, meaning this water level should be reached or exceeded every 46 years, on average. Galveston should observe 21 events like Ike (or more severe) in a 1000-year period.

We used a random number generator to select 21 unique flood years in a millennium and then placed a moving 30-year window over these data to determine how many 30-year periods were free of such floods and how many were inundated.

We determined that buildings in the 46-year flood plain have a 47% chance of being inundated during the life of a 30-year mortgage. This means that homeowners that signed 30-year mortgages in 1993 and were flooded by Hurricane Ike were undertaking at least a 47% chance of this flood during the life of their mortgage, as Ike was a 46-year event that struck during the median year (2008) of their mortgage. These values are accurate for the edge of the floodplain, while likelihood of flooding would increase as elevations decrease from that edge.

If Ike generated a storm tide 11.12 feet above Mean Sea Level for 2008, this level was 11.29 feet above Mean Sea Level for the year 2000, according to long-term linear sea-level rise trends. The intermediate-high sea-level rise projection, which initiates in the year 2000 (Table 5), increases the sea level by approximately 1.63 feet from the years 2000-2035. This means that a hurricane striking in the year 2035 only needs to generate a storm tide of 9.66 feet to equal the same total water level that Ike (2008) reached, decreasing Ike's total water level from a 46-year event to a 28-year event.

We should observe 35 events in a millennium that inundate the 28-year flood plain. Using the same methodology of a random number generator and a moving 30-year mortgage window, we estimated that the chance of inundation in Ike's flood plain will increase to 64% for 30-year mortgages initiated in the year 2020 (Table 13 and Figure 22).

This means if a homeowner buys a house flooded by Ike, and observed sea level rates match the intermediate-high sea-level rise projection, homeowners purchasing in the year 2020 face a 64% chance of that a storm tide will inundate their home to the same level of Ike within a 30-year mortgage. If a building observed several feet of water in Ike, the chance of floor board inundation in a 30-year mortgage is greater than 64%.

These statistics may shock Galvestonians, as many residents consider Ike an outlier flood that may only happen once in a lifetime. What is particularly shocking is that Ike's flood waters reached 12 feet above NAVD88, exceeding the Base Flood Elevation (BFE) in many places. For much of Galveston, the BFE is 11 feet above NAVD88. FEMA requires federally-backed mortgages to elevate to BFE, therefore, many residents would consider the BFE to be a level beyond which they are not vulnerable to flooding, or at least flood risk dramatically decreases.

As BFE is a water level that impacts the decision making of many residents, we ran statistics on the likelihood of flooding beyond BFE during the life of a 30-year mortgage. We determined that a storm tide of 10.12 feet would have been required to raise water levels to BFE in the year 2008, as Mean Sea Level reached 0.69 ft above NAVD88 in 1999, and the linear sea-level trend rose water levels an addition 0.19 ft from 1999-2008. These adjustments mean that a storm tide only needed to reach 10.12 feet for the total water level, including sea-level rise, to reach 11 feet.

Using the same approach as the Hurricane Ike analysis, we determined that the BFE level on Galveston Island equaled the 33-year flood level in 2008, but the 20-year flood level in 2035, given intermediate-high sea level rise. Homeowners initiating a mortgage in 1993 (median mortgage year 2008) faced a 56% chance of inundation during their mortgage, while homeowners initiating a mortgage in 2020 will face an 83% chance of inundation during the same 30-year mortgage (Table 13 and Figure 22) if their first-floor elevation matched the BFE requirement.

Probability of Flooding during a 30-year Mortgage		
Flood Level	Mortgage Initiated in 1993	Mortgage Initiated in 2020
Hurricane Ike (2008)	47%	64%
Base Flood Elevation	56%	83%

Table 13. Probability of flooding during a 30-year mortgage from water levels equaling Hurricane Ike (2008) and Base Flood Elevation. If homeowners are at edge of these floodplains these numbers equal the chance they will flood during a 30-year mortgage initiated in 1993 or 2020.

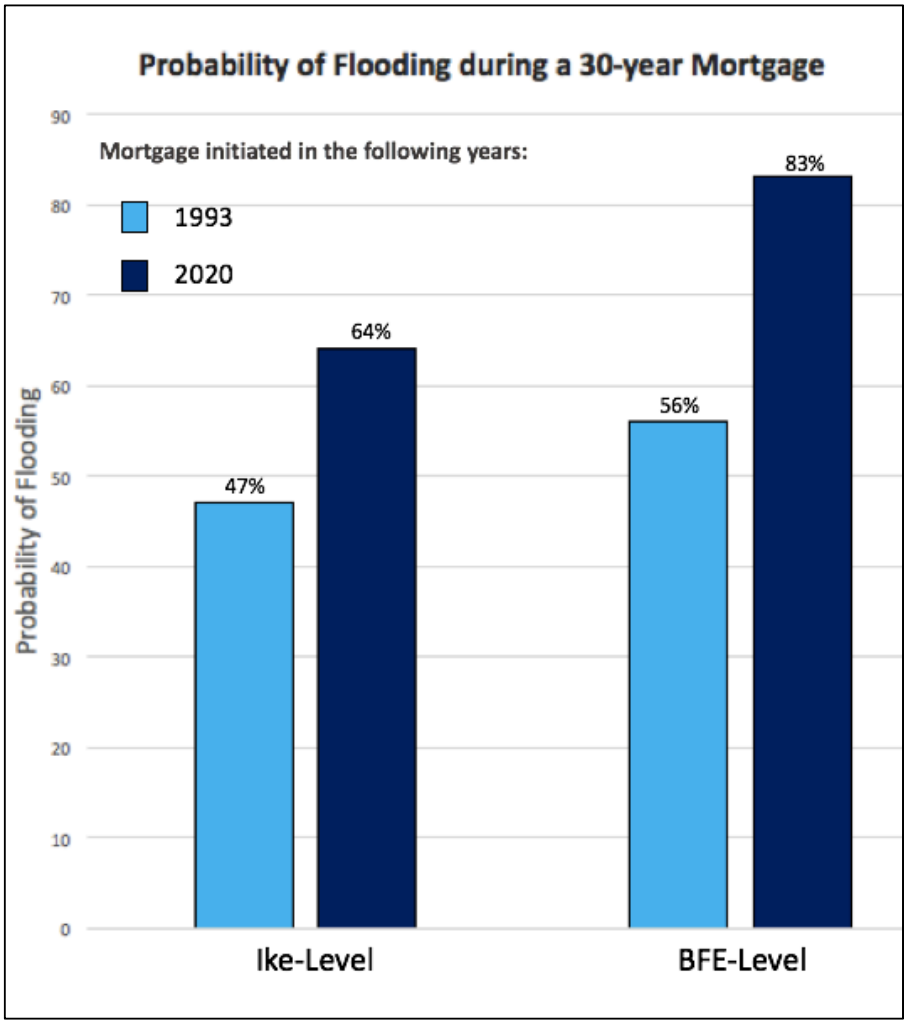

Figure 22. Probability of flooding during a 30-year mortgage initiated in 1993 or 2020. Ike-level is the flood level of Hurricane Ike (2008), BFE-level is the level of Base Flood Elevation, required by FEMA. Change in flood risk is due to sea-level rise under intermediate-high sea-level rise scenario. Graph relates to households in the Ike or BFE floodplains.

Although we have not conducted social science surveys as part of this project, Galveston residents would likely be surprised by the high frequency of flood events exceeding both Ike- and BFE-level floods during a 30-year mortgage. The local perspective generally assumes that houses raised above the BFE level are out of the flood plain and unlikely to experience inundation. In reality, this study shows that both Ike- and BFE-level floods are likely to occur during a 30-year mortgage.

Approximately 27% of buildings in our study area are elevated at or below Ike's flood level, while 21% are elevated at or below the BFE level. As our study area is located between Broadway and Seawall Boulevard, on middle to high ground compared to the rest of the island, these levels should cause concern. The ground north of Broadway is considerably lower and unless buildings are raised to higher levels they will be more vulnerable to flooding.

VIII. c. Applications for Historic Preservation

Applications of this research for historic preservation are important for Galveston, as the city contains a large collection of historic architecture from the Civil War era, Victorian era and early 20th Century. The city contains three historic districts and numerous buildings on the National Register of Historic Places. As historic districts often receive a disproportional amount of attention and resources for preservation, we intentionally chose a project area that receives less focus. Nonetheless, our study area borders the Silk Stocking Historic District and is located within a few blocks of several buildings on the National Register of Historic Places.

Preservationists can compare a building's first-floor elevation with the extreme water levels presented in this study to extend flood risk analysis to any historic buildings in the city. Such analysis is possible because our study used a "bathtub" model that considered vertical water displacement from storm surge and sea level rise, but did not model the dynamic flow of water. Therefore, two locations with the same elevation are given the same vulnerability to flooding in this study, regardless of their geographic location.

We analyzed flood risk for one building that is located less than a block from the northern boundary of our study area. Lasker Home for Homeless Children, also known as McLemore House, is a Greek Revival style building on the National Register for Historic Places (Figure 23). Using the methodology developed in this study, we determined that the ground elevation for this property is 7.73 feet (converted to year 2000 elevation) and the building is elevated 8.3 feet above the ground, providing a first-floor elevation of 16.03 feet.

This elevation places it outside the current 100-year floodplain but inside the floodplain for the 1900 Storm if that event were repeated today. However, sea-level rise will threaten this building with more frequent inundations in the future. According to the intermediate-high sea-level rise projection, the first floor of this building will be in the 100-year floodplain in 2050 and the 25-year floodplain in 2100. Such results can be repeated for any building in the city and will hopefully make the impacts of sea-level rise more relevant to those who value historic preservation.

Figure 23. Lasker Home for Homeless Children is a Greek Revival style building on the National Register of Historic Places. Although it is out of the current 100-year floodplain, it will be within the 50-year floodplain in 2050 and the 25-year floodplain in 2100 if the intermediate-high sea-level rise scenario verifies.

IX. Data Sharing and Outreach

An important component of this project involves data sharing and outreach. These activities ensure that this project benefits Galveston residents and professionals improving flood adaptation in Galveston and the Southeast Texas region.

Data sharing fits within a broader collaboration with the City of Galveston. From the beginning of this project, we have had support from the Mayor's office, as well as the division of Planning and Development with the Department of Development Services.

Catherine Gorman, the division's Assistant Director and Historic Preservation Officer, provided important direction early in this project to help us select the optimal study area. She chose an area where the city is attempting to build new datasets to improve planning efforts.

We met several times with Ms. Gorman during the life of this project to share data and ensure that our approach providing useful information for the City. Dustin Henry, the city's new Coastal Resource Manager, also became involved in this project to provide a unique perspective on the coastal aspect of this work.

Outreach events will be important to share project results with the broader Galveston community. We will partner with existing groups already planning outreach events to leverage their resources, momentum and public interest.

In these outreach events, we are interested to receive feedback on the following questions:
1) What are the most effective adaptations the City of Galveston and Galveston residents can make to protect themselves from future flooding?
2) How do the results of this study help inform the larger discussion about regional flood protection projects?
3) What is the best use of the interactive web-tool we built? Do residents favor an open web-tool or something more private, as the tool provides future flood projections at the property level.

We have scheduled a public outreach event for Thursday, May 17, 2018, in coordination with the University of Texas Medical Branch Center in Environmental Toxicology (UTMB/CET), a world leader in public health research and outreach efforts. The outreach event will be part of the Sci Café series, held monthly at Mod Coffee House.

We have also been invited to present results at a monthly Galveston Alliance of Island Neighborhoods (GAIN) meeting. GAIN provides a forum for local communities within Galveston to share information, and GAIN's 2018 Secretary, Jonathon Tromm, has invited us to present results from this study at an upcoming meeting.

We have also been in contact with the San Jacinto Neighborhood Association (SJNA) because our project area overlaps with the San Jacinto Neighborhood. Angela Brown, President of SJNA, is interested in having us share about this project at a neighborhood association meeting. The SJNA will discuss this during their January meeting and is interested in setting up an outreach event during the spring, when people are thinking more about flooding, as hurricane season approaches.

As of March 5, 2018, this report has been sent via e-mail attachment to personnel with at least 15 organizations, including the following:

- City of Galveston
- Galveston Historical Foundation
- U.S. Army Corps of Engineers- Galveston District
- Galveston Bay Foundation
- Texas A&M Galveston
- Rice University – SSPEED Center
- Galveston Alliance of Island Neighborhoods (GAIN)

- NOAA Flower Garden Banks National Marine Sanctuary
- National Weather Service
- Mississippi-Alabama Sea Grant (NOAA)
- Texas Sea Grant (NOAA)
- City of Mandeville, Louisiana
- Adaptation International
- Wharton School of Risk Management
- Broward College, Fort Lauderdale, Florida
- Texas Floodplain Management Association
- The American Shore and Beach Preservation Association (ASBPA)

A copy of this report has been uploaded to the U-Surge website for easy access. It is located under the products tab and research sub-tab at the following link: https://www.u-surge.net/research.html.

X. Future Efforts

This project was designed to operate as a pilot project to test the feasibility of using Google Earth and Google Street View for first-floor elevation mapping and flood risk assessment. Future efforts to expand the reach of this project may take on both geographic and conceptual components.

Geographically, this project could extend to additional areas of Galveston and other coastal cities. The sloped nature of Galveston Island provides an ideal test site for future versions of this study because the Island contains a wide range of ground elevations within a relatively short distance. Future mapping efforts may engage with communities north of Broadway, for example, where ground elevations are lower. Extending this study to that area would help us understand if the increased height of raised houses in this area offsets the lower ground elevations in relation to flood risk.

Conceptually, the project could extend into new areas as well. A study on the economic impact of floods in Galveston would provide context for making flood protection decisions. The web-mapping tool we developed provides water depths inside homes for different flood scenarios, providing a key first step in economic loss analysis. The U.S. Army Corps of Engineers provides depth-damage curves to estimate economic losses from floods of different levels, a concept that ties in very well with our prediction of future flood levels.

This type of research would connect flood scenarios with dollars and cents lost, helping Galveston assess economic risk from future floods and providing a framework for improved decision making.

Through the life of this project, many people have inquired about the feasibility of automating the FFE estimation procedure. Successful automation of this method could enable such analysis to cover larger areas in less time, perhaps allowing for FFE maps of entire cities.

Such efforts would be easiest in planned neighborhoods where cookie-cutter houses resemble each other. In historic communities, like Galveston, older buildings are unique from one another, making it more difficult to train a computer to see the level of the first habitable floor.

However, it is possible that computers could be trained to detect the dark-light-dark vertical pattern on staircases, which often lead to the bottom of the first habitable floor. This is a topic for future research.

Social science research that analyzes the difference between real and perceived flood risk should be another topic for future research. Coastal residents commonly believe that they are above the reach of flood waters if their home is elevated to the Base Flood Elevation (BFE), however, this study found that houses elevated to that level are still likely to flood in a 30-year mortgage cycle beginning in the year 2020.

Research focused on flood risk perceptions may benefit from analyzing the difference in residents' perception of flood risk from equally severe floods presented in different language. Flood risk is commonly communicated by return period (i.e. 100-year flood) or annual flood probability (i.e. 1% chance of annual flood), but these metrics may not be optimal, as they do not match the time window of mortgages or home occupancy. Flood risk communicated as likelihood of inundation over a 30-year window may provide a drastically different, and improved, perception of flood risk.

Applications for this research are numerous in city planning, civil engineering projects, and various flood protection initiatives (elevating houses). Residents of Galveston should take to heart the extreme urgency of flood risk.

The results of this study should place increased urgency on present-day flood adaptation solutions. These options include massive civil engineering projects, like the Galveston Ring Levee or Ike Dike/ Coastal Spine. They also include smaller-scale initiatives to elevate houses or promote better flood-proofing options, and make a strong case to take action sooner rather than later.

Galveston's high level of flood risk may also encourage local leadership to employ creative solutions for flood mitigation, in the same spirit of Galvestonians following the 1900 Storm. These initiatives may involve creative ways to live with the water instead of fighting against it, such as the acceptance and promotion of amphibious architecture as a retrofit option for historic homes, or making plans for yacht club and marina expansion to accommodate an increasing number of houseboats that rise and fall with changes in water levels.

Such perspectives should inform the decisions of all community planning efforts. The initiative to plant hundreds of live oak trees along Broadway after salt water from Hurricane Ike killed them reveals a local perspective that Ike generated an outlier storm surge that will not soon be repeated. Unless major civil engineering projects protect the city from rising seas and storm surges approaching from the harbor side, such planting efforts will be judged wasteful, as saltwater floods become more common in the future.

Finally, this pilot project sets a precedent for data-driven flood risk analysis in any coastal city. These efforts could be reproduced in other coastal communities that have adequate high water data and sea-level rise projections, as nearly every community is now on Google Street Earth and Google Street View. This seminal project will hopefully lead the way for improved flood risk analysis and decision making in areas most vulnerable to coastal flooding.

XI. Summary and Conclusion

This project provides an innovative methodology for estimating flood losses from present and future coastal floods. Our approach is innovative because the analysis primarily relied on data-driven methods for both analyzing housing inventory and flood levels.

The First Floor Elevation (FFE) analysis was achieved through a process we pioneered, using Google Street View and Google Earth imagery. This methodology has not been previously employed for this type of analysis, and our field work proved that we developed an accurate approach. Using data from 22 field sites, we confirmed that our method had a cumulative R^2 value of 0.9825 when compared to actual observations. Across these sites our method had a cumulative bias of -0.95 inches, meaning our methodology had a slight bias to underestimate building elevations, but this bias was less than one inch, on average.

We used this methodology to estimate FFE for 479 buildings in a 40-block area of Galveston. More than 90% of the buildings in our study area were residential, with the remaining buildings comprised of sheds/garages, schools, commercial and religious buildings.

We conducted a data-driven storm surge analysis, based on observed storm tide levels from the U-Surge project. These high watermarks were converted to the NAVD88 datum, providing the first comprehensive storm tide dataset available for statistical analysis at Galveston. We analyzed extreme water levels based on a log-linear regression (Gumbel Distribution) on high water marks from 93 hurricanes and tropical storms since 1900.

We combined these water levels with various sea-level rise scenarios to estimate present and future flood risk. Using projections from the National Oceanic and Atmospheric Administration, we selected intermediate and intermediate-high sea-level rise scenarios for our analysis.

When superimposing present and future flood levels on current building elevations, several patterns emerged. Building inundations from high-magnitude/ low-frequency floods increase more from 2000-2050 than from 2050 to 2100, as the percentage of inundated buildings is capped near the 100% level in the second half of the century. By contrast, the number of buildings inundated by the 10-year flood increases slowly from 2000-2050 and rapidly from 2050-2100.

Flood risk analysis for homeowners initiated 30-year mortgages in the year 2020 revealed particularly worrisome results. We found that homes inundated by Hurricane Ike (2008) with mortgages initiated in 1993 had a 47% chance of flooding in Ike, but this probability increases to 64% for mortgages initiated in 2020, given intermediate-high sea-level rise. Likewise, buildings elevated to the FEMA-required Base Flood Elevation (BFE), 11 ft for much of the city, had a 56% chance of flooding in a 30-year mortgage initiated in 1993, but an 83% chance of flooding during a mortgage initiated in 2020, given intermediate-high sea-level rise.

These results are of great concern to Galveston, as 27% of the buildings in our study area are at or below Hurricane Ike's flood level and 21% of the buildings are not elevated as high as BFE. This is troubling, because our study area contains higher-than-average ground on Galveston Island. Hopefully, this study will generate local interest and encourage urgent action to protect our project area, and all of Galveston, from future floods.

XII. Acknowledgements

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Appendix A.
Detailed Methodology for Estimating First Floor Elevations

1. Open file named Block_Data_170801. This file contains elevation data.
2. The project will generate data for a 40-block area. Scroll through the data and find a block that has not yet been mapped.
3. Open the file FFEMP_MAP_170801.pptx and find the location of your block. Then go to the slide that provides ID numbers for every building in your block.
4. Open Google Earth. Zoom into your street in Galveston, Texas.
5. Drag the "orange man" from the right of the Google Earth screen to a position in front of a building. Note: Please do this in Google Earth, not Google Maps. Sometimes there is a difference between the two mapping sources. It appears that Google Earth is more accurate. If possible, do it in Google Earth Pro (you may need to download that...it should be free).
6. When you arrive at Google Street View in Google Earth, "pan" to the left or right to see your building. IMPORTANT: Use the left or right arrows on your keyboard to pan left or right. This keeps the camera angle at a constant level. If you click and drag to move camera to right or left, it is possible that you will change the camera angle and this can cause errors.
7. Position the camera so you can clearly see your building. You may need to slightly move up or down the street for the optimal view. You can do this by clicking on the yellow line that is visible when you look down the street. When the camera is turned toward your building, you may zoom in on your building as far as possible, as long as you can still see the roof line and building elevation. Note that the camera should always point perpendicular to the street edge. It's ok if your target house is not in the center of the camera view- it may be offset to the side.
8. Find a method to measure pixels on your computer screen. If you are using a Mac, use the function for a screenshot, COMMAND-SHIFT-4. Once you enter this, you will see crosshairs on the screen, with two small numbers. These numbers are X and Y coordinates on the screen. You can use these coordinates for measuring pixels. If you do not have a Mac, you may need to download a software or find another method to measure pixels on your computer screen.
9. Measure the distance, in pixels, of the vertical elevation that the building is raised above the ground. The two points you choose must be in the same vertical plane. It is common that you may choose the elevation of a front porch, on the edge that is closest to the street. Then the ground elevation must be directly below (vertically) this point. Note that the top of the vertical distance is often the front edge of a porch that is closest that is closest to the street. The surface of an elevated porch is considered the first floor elevation, even though it is usually several inches lower than the front door.
10. Measure the distance, in pixels, of the roof line on your building. IMPORTANT: You want to measure the horizontal roof line, looking from left to right across the screen. You must measure the roof line that is in the same vertical plane as the building elevation you can measure. In other words, if you measured the building elevation at the street edge of

the porch, then you must also measure the roof line that is directly above (vertical) this elevation line.

11. Once you have the vertical and horizontal pixel distances, subtract them and enter them in the file, as columns E (vertical pixels) and B (horizontal pixels).
12. Zoom out of Google Street View. Now you are looking down at your building from above. Zoom into your building, while keeping the angle of the image vertical. If you zoom in too far, Google Earth wants to take you to Google Street View again. It takes some playing with the controls to get an air photo zoomed in a fair amount, but not so far that it takes you to Google Street View. Controls on the right side of the screen enable you to adjust the camera vertically, which is optimal.
13. Select the measuring tool at the top of Google Earth. Choose units: inches.
14. Measure, in inches, the same roof line that you measured in pixels on Google Street View.
15. Enter this value in column C.
16. Measure the ratio of pixels to inches. You want to know how many inches each pixel represents. Use this equation.... PIX_Ratio = Roof Inches (column C) / Roof Pixels (Column B). Enter the answer in Column D. The ratio usually ranges from 0.30 to 0.85. The ratio so far has always been less than 1.
17. Now we know the ratio of pixels to inches in the vertical plane, and we know the number of pixels that the building is raised above the ground.
18. We now want to calculate the distance that the building is elevated in inches. Multiply column D by column E, to find this value. Enter the value of building height in inches in column F. You used steps 1-18 to estimate the first-floor elevation above ground, in inches.
19. If possible, count the number of stairs between the ground and elevated first floor. Note: Sometimes “half stairs” are visible. A “half stair” exists when distance of the first or last (or both) stairs are noticeably less than the distance of the other stairs. Enter the number of stairs in column H.
20. Multiply the number of stairs in column H by a value of 7.5 and input this value in Column I. In general, the distance between stairs should average about 7.5 inches, so column I is an estimate of the building elevation based on number of stairs. However, sometimes stair distances vary. The stair elevation estimate will usually differ than the Google Earth/ Google Street View estimate, however, these values should be within about 30% of each other. If your Google Street View method gives you an elevation of 93 inches and the stair method gives you an elevation of 26 inches, there may be a mistake. More likely, if Google Street View gives an elevation of 93 inches, the stair method will range from around 65-120 inches, give or take.
21. Enter the street from which you used Google Street View in Column J. For corner buildings make sure you are listing the street from which your view originated.
22. Enter the building type in column K. Most buildings will be residential. Some on the outside (facing street) will be garages, commercial, religious or industrial.
23. Simply repeat this process for all buildings in your block and then move on to a new block.