The Impact of Pumping and Sandbagging by the City of Lake Jackson on Flooding in the City of Richwood and other County Areas following Hurricane Harvey

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LIGHTNING SUMMARY

Following Hurricane Harvey (August 2017), the City of Lake Jackson (Texas) used pumps and a sandbag dam to block the overflow of Bastrop Bayou from the north. Although the pumping was ineffective, the sandbag dam diverted 27.7 billion gallons of water through the city of Richwood, which would have been enough to cover the flood-affected area to a depth of 46 feet. Based on watermarks on houses and fences, Richwood was flooded to an average depth of two feet, so that about 96% of the diverted water eventually reentered Bastrop Bayou.

ABSTRACT

Following Hurricane Harvey (August 2017), the City of Lake Jackson (Texas) used pumps and a sandbag dam to block the overflow of Bastrop Bayou from the north. The pumping was ineffective because a flap gate in the pumping chamber was held open by debris, which allowed the return of water at a rate that exceeded the maximum pumping rate. The above calculation by the expert witness for Lake Jackson was based on the observation by City of Lake Jackson personnel that the water level on the north side of the open gate was at least one foot higher than on the south side throughout the period of pumping. Consistent with the above observation and with photos of the sandbag dam, it is likely that the water elevation was at least one foot higher on the north than on the south side along the entire 2000-foot long sandbag dam. Using the Rectangular Weir Equation, the interception by the sandbag dam was equivalent to a row of pumps that would have been pumping water from south to north at 4.8 million gallons per minute (gpm), for a total of 27.7 billion gallons of water for the four days of sandbagging, which would have been enough water to cover the flood-affected area to a depth of 46 feet. The 2018 Lidar data, drone videos taken during the flooding, and post-flooding ground photos were used to reconstruct the path of the flood wave into the neighboring city of Richwood and eventually back into Bastrop Bayou. Based on watermarks on houses and fences, Richwood was flooded to an average depth of two feet, so that about 96% of the diverted water reentered the bayou after passing through Richwood. The home flooding times reported by the residents are consistent with the reconstructed flood path, and not with a simple overflow of Bastrop Bayou without the intervention of a sandbag dam. Measured watermarks and water-surface elevations were also consistent with the reconstructed flood path, but not with the output of a HEC-RAS model that was used by the expert witness for Lake Jackson. The failure of the HEC-RAS model was probably caused by a combination of outdated topography, lack of knowledge of the magnitudes of extreme events on Bastrop Bayou (an ungaged stream), and the assumption of steady-state flow (as opposed to a time-progressive flood). According to the expert witness for Lake Jackson,

the flooding of Richwood was caused by an overflow of the Brazos River into Oyster Creek and then into the watershed of Bastrop Bayou, which was inconsistent with the lack of flooding of municipalities along Oyster Creek, including Holiday Lakes, Bailey's Prairie, and Lake Jackson itself. Moreover, an origin of the flood in the Brazos River, which is well-known for its muddy water, is inconsistent with the very clear flood water in Richwood that is evident in ground photos and drone videos. On the above basis, the sandbag dam, but not the pumping, was certainly responsible for the flooding in the city of Richwood and other county areas.

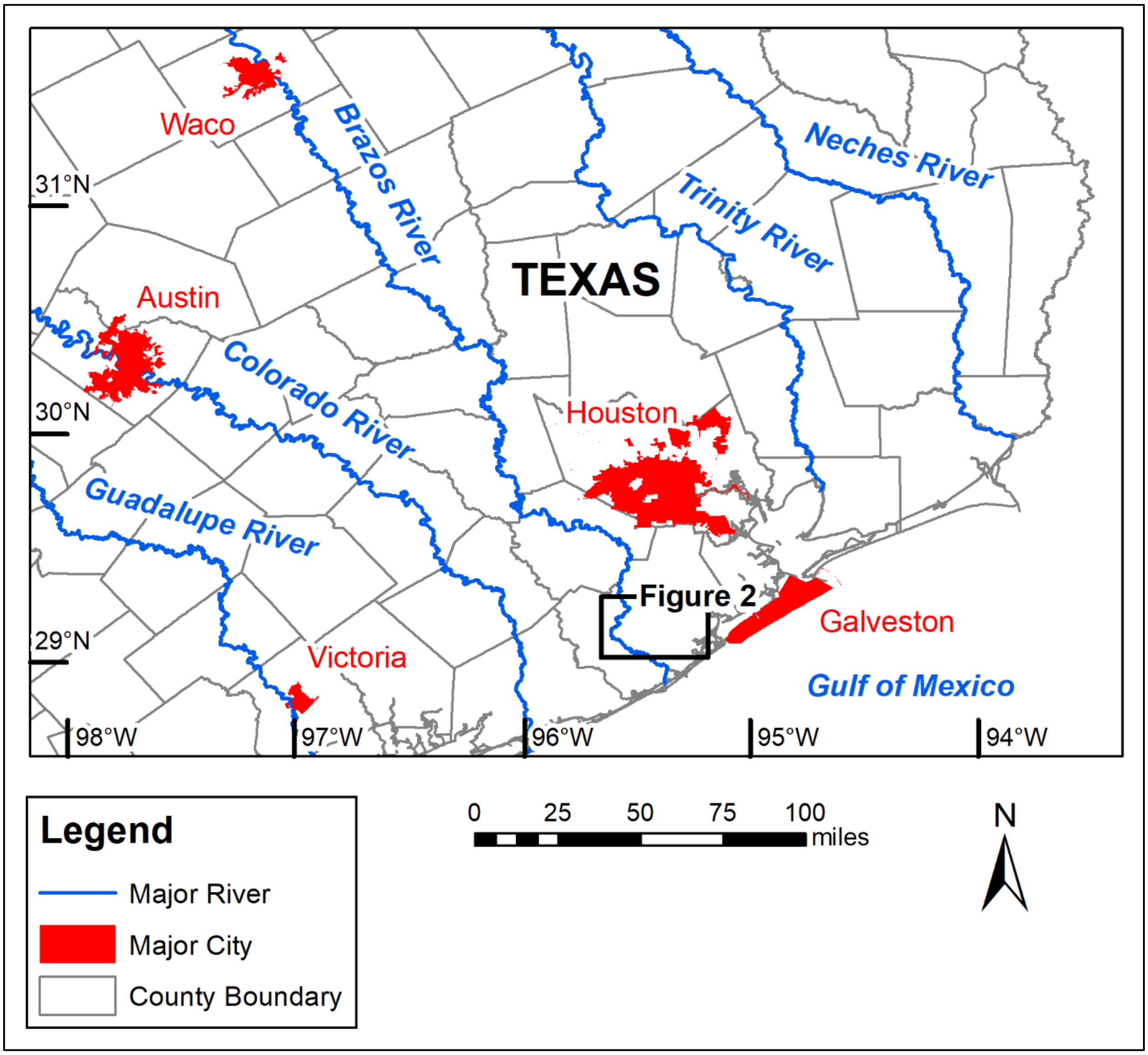

Figure 1. The cities of Lake Jackson and Richwood are located south of Houston, Texas, and east of the Brazos River.

INTRODUCTION

Following Hurricane Harvey in August 2017, the City of Lake Jackson (Texas) used both pumps and a sandbag dam to block the overflow of Bastrop Bayou across Highway FM2004 (see

Figs. 1-3). Subsequent to the actions of the City of Lake Jackson, flooding occurred in the city of Richwood to the east and in other county areas outside of Lake Jackson (see Fig. 3). The 24-inch high, 2000-foot long sandbag dam was constructed across the south side (eastbound lanes) of FM2004 and the north side of the FM2004 south frontage road, and was in place from August 31 to September 3, 2017 (see Figs. 4a-c). The pumping was carried out in an attempt to transfer water from the Brazos Canal (also called Slave Ditch) into Bastrop Bayou (see Fig. 3). The Brazos Canal typically flows northward into a pumping chamber that is south of FM2004, through culverts that pass under FM2004, and then northward to Bastrop Bayou (see Figs. 3, 5a-d). However, when Bastrop Bayou is at flood stage, water could flow in the opposite direction, that is, southward from Bastrop Bayou, through the culverts under FM2004, and into the pumping chamber (see Figs. 3, 5c-d). The pumping chamber includes three flap gates that allow water to flow only northward, so that water from Bastrop Bayou cannot flow southward through the Brazos Canal into Lake Jackson (see Fig. 5c). From August 27 until September 11, 2017, five pumps were used to transfer water from the Brazos Canal into the pumping chamber in an attempt to force the water to flow into the culverts and northward across the highway (see Fig. 5e).

The objective of this report is to answer the following questions:

1) Did the pumping more likely than not cause the flooding of Richwood and other county areas outside of Lake Jackson?
2) Did the placement of the sandbag dam more likely than not cause the flooding of Richwood and other county areas outside of Lake Jackson?
3) Did the combination of the sandbag dam and the pumping more likely than not cause the flooding of Richwood and other county areas outside of Lake Jackson?
4) Could the impacts of pumping and/or the placement of the sandbag dam have been predicted at the time?

Before addressing the methodology for answering these questions, I will first summarize the report by the expert witness for the City of Lake Jackson (Grounds, 2019).

EXPERT REPORT FOR CITY OF LAKE JACKSON

The expert witness for the City of Lake Jackson concluded that none of the actions of the City of Lake Jackson were responsible for the flooding that occurred in the city of Richwood and other county areas outside of Lake Jackson (Grounds, 2019) and offered an alternative explanation for the flooding. Grounds (2019) first considered the impact of pumping. From noon on August 28 until 4:50 pm on August 31, one of the flap gates was held open by debris at a 45° angle, which allowed water to flow southward out of the pumping chamber and back into the Brazos Canal (see Fig. 5e). According to Grounds (2019), "The head and tailwater conditions during the pumping varied. A minimal observed difference by the City of Lake Jackson personnel in the water surface elevations on both sides of the gate was 1 foot. For most of the duration of the pumping, this difference was greater and would allow for more water to pass in reverse through the gate." Grounds (2019) then used the observed minimum water-elevation difference of one foot (higher on the north side) to calculate that water was flowing through the partially open flap gate at 20,540 gallons per minute (gpm). By contrast, the maximum combined pumping rate from five pumps during the same period was 10,257 gpm. After the flap gate was closed, only three pumps were operated at a combined rate of 2047 gpm. On the above basis, Grounds (2019) concluded that, at least until the late afternoon of August 31, the pumping was completely ineffective in that water was flowing southward and out of the pumping chamber faster than it was being pumped back into the pumping chamber. Although not explicitly stated by Grounds (2019), it should be clear that the high water level in the pumping chamber (see Fig. 5e) resulted not from the pumping, but from the southward flow from the Brazos Canal and through the culverts under FM2004.

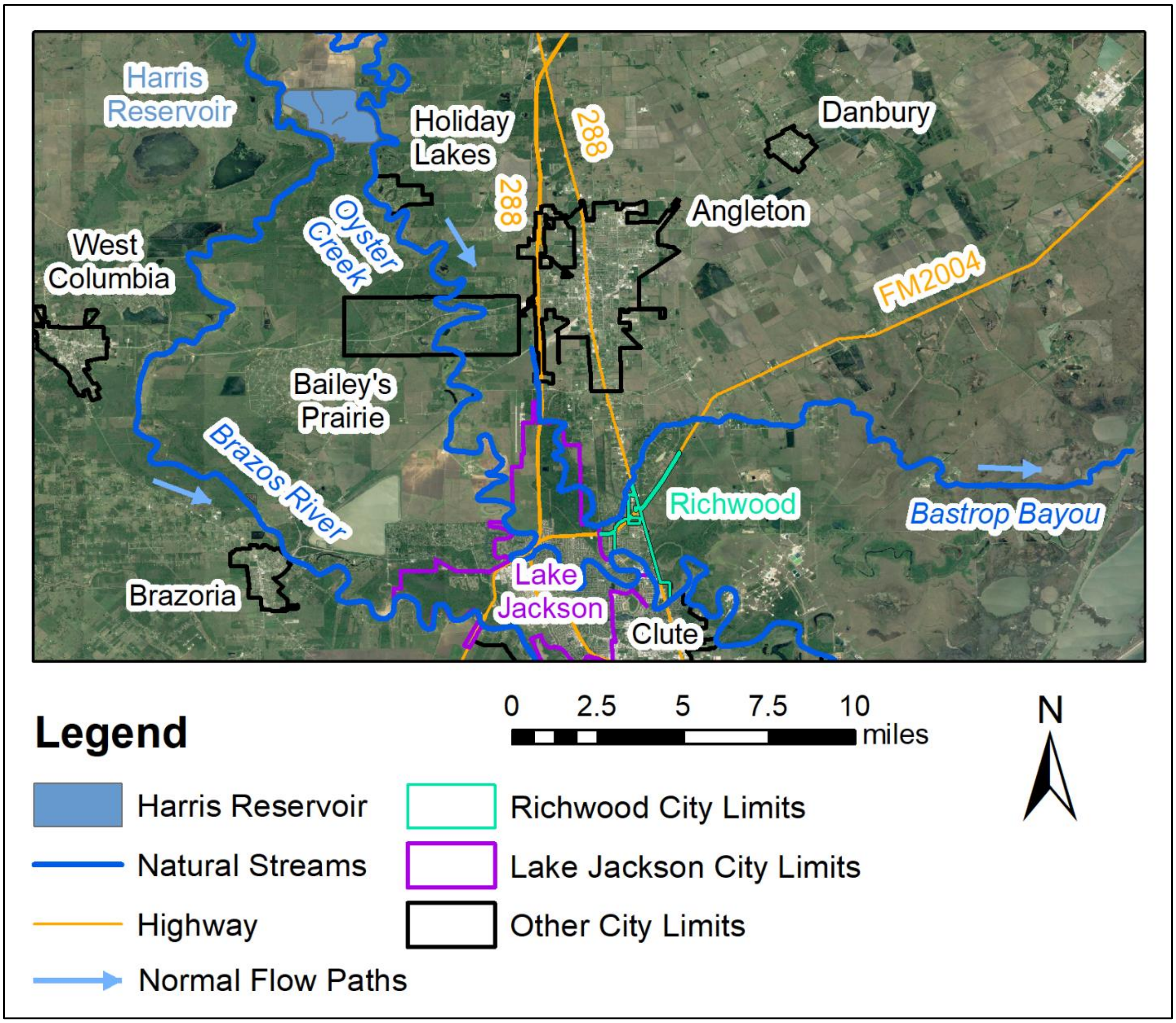

Figure 2. According to Grounds (2019), the source of the flooding of the city of Richwood was the overflow of the Brazos River into Oyster Creek near the Harris Reservoir. This overflow crossed Oyster Creek and entered the watershed of Bastrop Bayou. However, if this sequence of events had occurred, flooding would also have occurred all along Oyster Creek, including Holiday Lakes, Bailey's Prairie, Lake Jackson, and parts of Angleton (depending upon where the flood entered the watershed of Bastrop Bayou). Moreover, since the Brazos River is well-known for its muddy water, the flood water in Richwood would have been muddy, as opposed to the clear flood waters that actually occurred (see Figs. 18, 19a-c, 20, 21). Note that the Brazos River, Oyster Creek and Bastrop Bayou are parallel streams that enter the Gulf of Mexico without intersecting. Note also that Hwy. 288 on the west (except for the very northern portion of the map) is the Nolan Ryan Expressway, while Hwy. 288 on the east is Brazosport Boulevard (compare with Fig. 20).

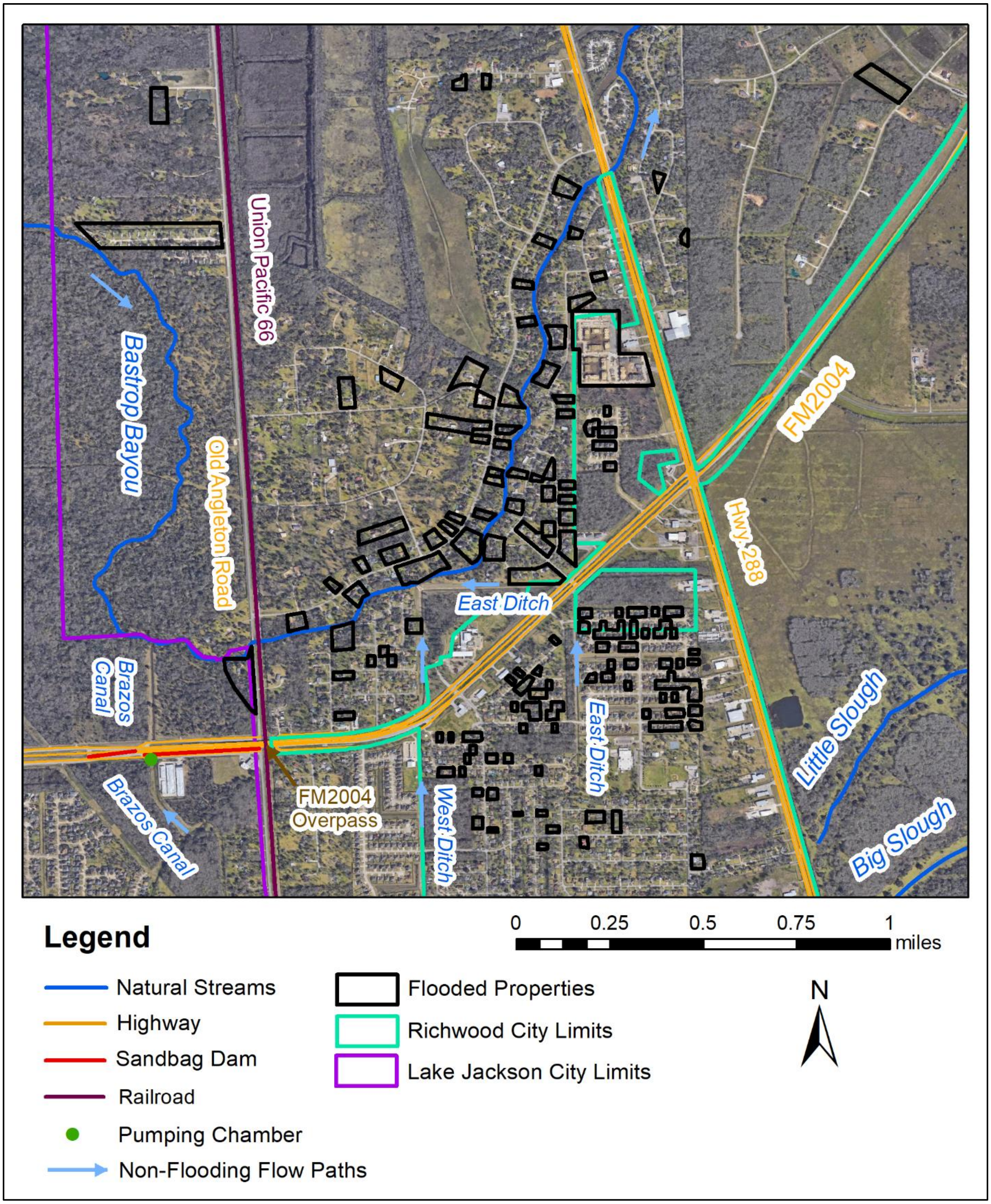

Figure 3. Following Hurricane Harvey, the City of Lake Jackson used pumps and sandbags to block the overflow of Bastrop Bayou from the north. Although the pumping was ineffective, the effect of the sandbag dam was to divert 27.7 billion gallons of water (see Fig. 6) through the city of Richwood and adjacent county areas. The indicated flow paths are typical for the Brazos Canal, East Ditch and West Ditch in the absence of overflow from Bastrop Bayou. "East Ditch" and "West Ditch" are names given by the author. Note that Hwy. 288 is Brazosport Boulevard, not the Nolan Ryan Expressway (compare with Fig. 20).

Figure 4a. A 24-inch high, 2000-foot long sandbag dam was constructed along the south side (eastbound lane) of FM2004 to prevent flooding of the city of Lake Jackson. View is looking east. Note FM2004 overpass over Old Angleton Road in background (see Fig. 3). Photo taken on or before September 3, 2017, and provided by Matías J. Adrogué, PLLC.

The HEC-RAS (Hydrologic Engineering Center – River Analysis System) software (U.S. Army Corps of Engineers, 2019) was also used to evaluate the impacts of both pumping and the sandbag dam. Grounds (2009) found that the reduced pumping after August 31 would have increased the flow rate along Bastrop Bayou by no more than 0.073% above what would have been expected during a 100-year flood and no more than 0.052% over what would have been expected during a 500-year flood. The same software showed that the combined effect of the sandbag dam and the pumping would have produced a non-observable impact on the water level in Bastrop Bayou (less than 0.01 feet) during either a 100-year flood or a 500-year flood. In light of the negligible impacts of pumping and sandbagging, the alternative explanation proposed by Grounds (2019) for the flooding of the city of Richwood and other county areas was an overflow of the Brazos River into Oyster Creek near the Harris Reservoir (see Fig. 2). According to Grounds (2019), this overflow would have crossed Oyster Creek and entered the watershed of Bastrop Bayou (see Fig. 2).

Figure 4b. A 24-inch high, 2000-foot long sandbag dam was constructed along the south side (eastbound lane) of FM2004 to prevent flooding of the city of Lake Jackson. View is looking west. Still shot at 1:00 of drone video labeled Before-8 taken on or before September 3, 2017, and provided by Matías J. Adrogué, PLLC.

METHODOLOGY

In light of the report by the expert witness for the City of Lake Jackson, before addressing the objectives of this report, it is necessary to answer the following questions:

1) How much water was diverted by the sandbag dam?
2) What was the path of the overflow from Bastrop Bayou after it was diverted by the sandbag dam?
3) Were the flooding times of homes in the city of Richwood and other county areas consistent with the projected path of the overflow from Bastrop Bayou?
4) Were the flooding times of homes in the city of Richwood and other county areas consistent with an overflow of the Brazos River into the watershed of Bastrop Bayou (Grounds, 2019)?
5) Were the measured water-surface and watermark elevations consistent with the output of the HEC-RAS model (Grounds, 2019)?
6) Were the measured water-surface and watermark elevations consistent with the projected path of the overflow from Bastrop Bayou after diversion by the sandbag dam?
7) Was the residential flooding in other municipalities (besides Richwood and adjacent county areas) consistent with an overflow of the Brazos River into the watershed of Bastrop Bayou (Grounds, 2019)?
8) Was the appearance of the flood water in the city of Richwood and other county areas consistent with an overflow of the Brazos River into the watershed of Bastrop Bayou (Grounds, 2019)?

Figure 4c. Former site of 24-inch high, 2000-foot long sandbag dam that was constructed along the south side (eastbound lane) of FM2004 to prevent flooding of the city of Lake Jackson. View is looking to the west. The foreground is the intersection of Old Angleton Road (left to right) and the FM2004 south frontage road (foreground to background). The intersection was the easternmost limit of the sandbag dam (see Fig. 3), which was constructed on the north side of the south frontage road (middle right side of photo). Note the FM2004 overpass over Old Angleton Road to the right (see Figs. 3 and 4a) and the Do Not Enter sign on the FM2004 exit ramp in the background. Photo taken by the author on October 30, 2019.

The central part of the hydraulic analysis is the role of the sandbag dam in the interception and diversion of water that was flowing out of Bastrop Bayou from the north. Every effort was made to address this question without the use of software, in order to make the assumptions and calculations as clear as possible. The key to this analysis is the observation by City of Lake Jackson personnel that the water surface on the north side of the partially open flap gate was at least one foot higher than on the south side (Grounds, 2019). It is important to note that this water-elevation difference persisted continuously, even during the 53-hour period when water was pouring through the gate from the north to the south. On that basis, it could be assumed that a similar minimum difference in water elevation (one foot higher on the north side than on the south side) occurred along the entire length of the sandbag dam (see Fig. 3). This assumption seems consistent with available photos of the sandbag dam (see Figs. 4a-b), although no available photo has the proper vantage point for directly measuring the difference in water elevation.

Figure 5a. Typically, water in the Brazos Canal (Slave Ditch) flows to the north toward Bastrop Bayou from south of FM2004 (see Fig. 3). View looking to the south on the south side of FM2004. Photo taken by the author on October 30, 2019.

The interception of water by the dam was calculated using the water-elevation difference across the dam (see Fig. 6). If the top of the sandbag dam had been set at the water elevation on the south side, then water would have flowed over the dam from the north to the south side. The dam would then have acted as a sharp-crested rectangular weir, that is, a hydraulic structure that is used to determine flow rates in canals or narrow streams based upon the difference in water elevations on either side of the weir (Chadwick et al., 2013). This relationship is given by the Rectangular Weir Equation

$$Q = \frac{2}{3} L \sqrt{2g} H^{3/2} \quad (1)$$

where Q is flow rate (also called discharge), L is the length of the weir, g is acceleration due to gravity, and H is the difference in elevation of the water surface across the weir. If the sandbag dam had not been present, Eq. (1) gives the rate at which water would have flowed from north to south across Highway FM2004 (see Figs. 3, 4a-b). On that basis, the sandbag dam could be regarded as a row of pumps that was pumping water from the south back to the north at a rate given by Eq. (1).

Figure 5b. Typically, water in the Brazos Canal (Slave Ditch) flows northward from the south side of FM2004 and through a set of three flap gates into a pumping chamber and then northward to Bastrop Bayou (see Fig. 3). View looking to the north. The purpose of the flap gates is to prevent water from flowing from the north through the Brazos Canal and into the city of Lake Jackson when Bastrop Bayou is at flood stage. From noon on August 28, 2017, until 4:50 pm on August 31, 2017, one of the flap gates was stuck open at a 45° angle, which allowed water to flow southward from Bastrop Bayou into the Brazos Canal south of FM2004. Photo taken by the author on October 30, 2019.

The pathway of the diverted flood water was determined using three types of information. The first was drone videos and ground photos that were taken during the flooding and which were provided by the law firm Matías J. Adrogué, PLLC. The second was ground photos that were taken by the author during a site visit on October 30, 2019, in the company of Kevin McKinney (resident of a county area just outside of Richwood) and the attorneys Matías J. Adrogué, Eric Nowak and Zeinab Kachmar Zahid. Finally, the most recent 1-meter DEM (Digital Elevation Model) that was developed using 2018 Lidar data (StratMap, 2018a-b) was extremely valuable. In this respect, it should be noted that the use of the HEC-RAS model by Grounds (2019) was based upon the topographic data given in FEMA (2018), which did not incorporate the Lidar data that is currently available (StratMap, 2018a-b). Moreover, the expert witness for the City Lake Jackson confirmed during the deposition on October 29, 2019, that he did not carry out a site visit except to take a photograph of the pumping chamber.

The drone videos, ground photos and Lidar data were supplemented with publicly-available data on locations of natural streams, waterbodies, highways, railroads and municipalities (Texas Department of Transportation, 2019; Texas Natural Resources Information System, 2019a-c) The background image used in the maps (see Figs. 2, 3, 8, 11, 16, 20) is the most recent image from Google Earth, dated March 21, 2018. The location of the pumping chamber, the length and location of the sandbag dam, and the locations of the flooded properties were obtained from the map (Exhibit 1) in Grounds (2019). Although the dam length was measured as 2000 feet from the map in Exhibit 1 (two red lines labeled "Sand Bagging Limits"), Exhibit 2 of Appendix A of Grounds (2019) showed a two-section dam consisting of a "Sand Bagging operation" with length approximately 1100 feet and a "Sand Berm Operation" with length approximately 1400 feet, for a total of 2500 feet. The length of 2000 feet was chosen for consistency of the length and location of the dam. The height of the sandbag dam was obtained from an e-mail sent by the City of Lake Jackson (2017). The timing of pumping and sandbagging, and the pumping rates were obtained from Grounds (2019).

Figure 5c. Typically, water in the Brazos Canal (Slave Ditch) flows northward from the south side of FM2004, through a set of three flap gates into a pumping chamber, through culverts under FM2004, and then northward to Bastrop Bayou (see Fig. 3). View looking to the east. The purpose of the flap gates is to prevent water from flowing from the north through the Brazos Canal and into the city of Lake Jackson when Bastrop Bayou is at flood stage. From noon on August 28, 2017, until 4:50 pm on August 31, 2017, one of the flap gates was stuck open at a 45° angle, which allowed water to flow southward from Bastrop Bayou into the Brazos Canal south of FM2004. Note the cables for manual opening of the flap gates, the pipes on the left side for direct pumping into the Brazos Canal on the opposite (north) side of FM2004 (see Fig. 5d), and the FM2004 overpass in the left background (see Fig. 3). Photo taken by the author on October 30, 2019.

Times of flooding in the street, yard and home were obtained from residents of the flooded properties and included 190 respondents. These data were obtained by the Richwood Advisory Council and provided to the author by Matías J. Adrogué, PLLC. Not all residents reported all information and the information had varying degrees of precision. In cases where a date, but no time, was specified, the time was assumed to be noon. Times reported simply as "am" or "pm" were assigned to 6:00 am and 6:00 pm, respectively. When times without "am" or "pm" were reported, they were assumed to be "pm." Out of the 190 responses, 40 (21%) were adjusted in one of the above ways.

Figure 5d. Typically, water in the Brazos Canal (Slave Ditch) flows northward from the south side of FM2004, through a set of three flap gates into a pumping chamber, through culverts under FM2004, and then northward (to the left of the photo) to Bastrop Bayou (see Fig. 3). View looking to the east on the north side of FM2004. The purpose of the flap gates is to prevent water from flowing from the north through the Brazos Canal and into the city of Lake Jackson when Bastrop Bayou is at flood stage. From noon on August 28, 2017, until 4:50 pm on August 31, 2017, one of the flap gates was stuck open at a 45° angle, which allowed water to flow southward (to the right of the photo) from Bastrop Bayou into the Brazos Canal south of FM2004. In addition to the culverts, note the three pipes for direct pumping of water into the Brazos Canal (see Fig. 5c). Photo taken by the author on October 30, 2019.

The database for comparing measured and predicted water-surface elevations was developed by combining information from Grounds (2019) with observations made during the site visit (see Table 1). Most of the homes in Richwood and adjacent county areas had already been power-washed at the time of the site visit, but the exceptions showed orange-brownish watermarks about two feet above the ground surface (see Fig. 7a). The fence in the backyard of 12 Sherwood Drive (property of Kevin McKinney) just outside of Richwood showed a watermark below which light-grayish lichens had been removed by the flood water (see Figs. 7b, 8). The average watermark along the fence was measured at 24 inches above the ground surface. Since the Lidar-based DEM (StratMap, 2018a) gave a ground elevation of 11.42 feet at the same location, the maximum water-surface elevation at the location was determined to be 13.42 feet (see Table 1). It should be noted that both the new Lidar data (StratMap, 2018a-b) and the elevations reported by Grounds (2019) were based on the same definition of sea level (NAVD88, Geoid 12B) (AECOM, 2018).

Figure 5e. Typically, water in the Brazos Canal (Slave Ditch) flows northward (from top to bottom in photo) from the south side of FM2004, through a set of three flap gates into a pumping chamber, through culverts under FM2004, and then northward to Bastrop Bayou (see Fig. 3). Note the three large blue pumps that are pumping water from the Brazos Canal and into the pumping chamber in order to force the water to flow northward through the culverts. The purpose of the flap gates is to prevent water from flowing from the north through the Brazos Canal and into the city of Lake Jackson when Bastrop Bayou is at flood stage. From noon on August 28, 2017, until 4:50 pm on August 31, 2017, one of the flap gates was stuck open at a 45° angle, which allowed water to flow southward out of the pumping chamber into the Brazos Canal south of FM2004. Based on the minimum drop in water level of one foot from the north to the south side of the flap gates (equivalent to the drop in water level from the inside to the outside of the pumping chamber), Grounds (2019) showed that water was flowing out of the pumping chamber southward into the Brazos Canal faster than it was being pumped into the pumping chamber. On that basis, the high water level in the pumping chamber resulted not from the pumping, but from the southward flow through the culverts. Still shot of drone video taken on or before September 3, 2017, and provided by Matías J. Adrogué, PLLC.

Grounds (2019) reported watermarks and water-surface elevations at two locations, which were the FM2004 north frontage road closest to the pump chamber and the upstream side of the bridge over Bastrop Bayou of Old Angleton Road (see Fig. 8). Watermarks on the FM2004 north frontage road were field-surveyed at 14.21 feet at 1:55 pm on August 31, 2017, and at 15.39 feet at 3:39 pm on September 1, 2017 (Grounds, 2019). The water-surface elevations at the Old Angleton Road bridge were reported as 14.0 feet at 2:37 pm on August 31, as 14.3 feet at 4:49 pm on August 31, and as 15.0 feet at 5:28 am on September 1 (Grounds, 2019). These water-surface elevations were "extrapolated from observed stream water surface elevations" (Grounds, 2019), which were not reported. The preceding information is taken from a table in Grounds (2019) entitled Time Line / Activities. Earlier, Grounds (2019) had written, "Based on the observed and surveyed high water mark (September 1, 2017) by the City of Lake Jackson personnel of 15.39 feet at the upstream side of Old Angleton Road (HEC-RAS Cross Section 84584.89)…," which contradicts the information in Time Line / Activities. It is most likely that the elevation of 15.39 feet refers to the FM2004 north frontage road (as stated in Time Line / Activities), since Bastrop Bayou should have been higher in the vicinity of the measurement point on the FM2004 north frontage road than at the Old Angleton Road bridge (see Fig. 8). Therefore, the information in Time Line / Activities (Grounds, 2019) was used in this report (see Table 1).

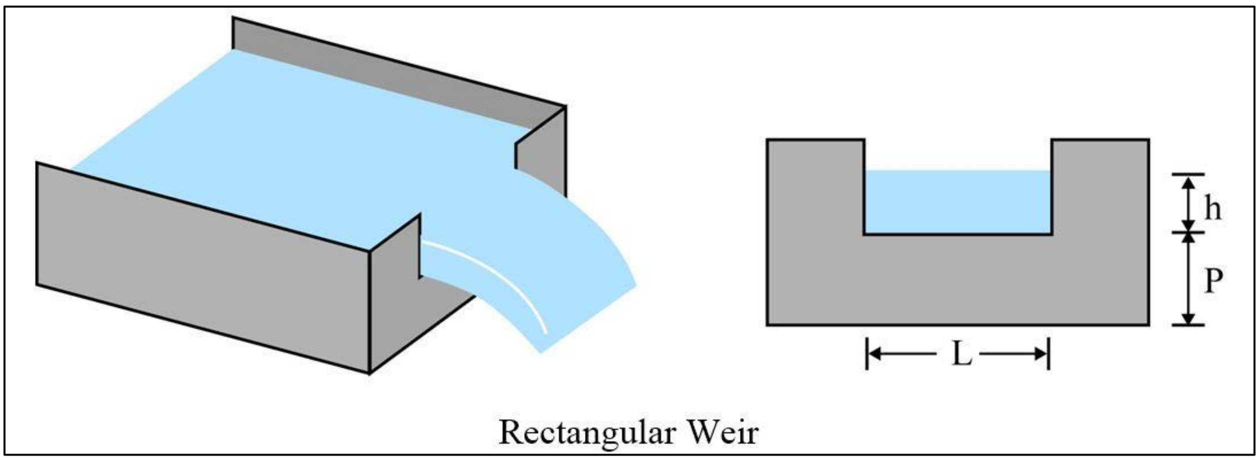

Figure 6. City of Lake Jackson personnel observed that, at a flap gate in a pumping chamber that was stuck open by debris (see Figs.3, 5c, 5e), the water elevation was at least one foot higher on the north than on the south side (Grounds, 2019). Consistent with the above observation and with photos of the sandbag dam (see Figs. 4a-b), it is likely that the water elevation was at least one foot higher on the north than on the south side along the adjacent 2000-foot long sandbag dam (see Fig. 3). If the height of the sandbags had been set at the water elevation on the south side, the water would have flowed from north to south (left to right in the figure) as if the sandbags were a rectangular weir. Using the Rectangular Weir Equation, the steady-state flow rate over the lowered sandbags would have been Q = 4.8 million gallons per minute. On that basis, the row of sandbags was equivalent to a row of pumps that would have been pumping water from south to north across the line of sandbags at Q = 4.8 million gallons per minute, for a total of 27.7 billion gallons of water for the four days of sandbagging. Figure from EPA Stormwater Management Model (SWMM5) and InfoSWMM Information for Watershed Water Quality, Hydrology and Hydraulics Modelers (2019).

At each of the two locations of watermarks and water-surface elevations reported by Grounds (2019), the maximum measured elevation was chosen for comparison with the predictions of the HEC-RAS model (see Table 1). This was done for consistency with the watermark at the McKinney fence, which was certainly a maximum elevation. Based on the above quote from Grounds (2019), it should be assumed that maximum water-surface elevations on both the FM2004 north frontage road and the Old Angleton bridge occurred on September 1, 2017. Moreover, it is necessary to choose a single water-surface elevation at each location for comparison with the HEC-RAS model, since the model run by Grounds (2019) was a steady-state model that did not take into account any changes through time.

Figure 7a. Homes in Richwood and adjacent county areas that were not power washed after the flood still show watermarks about two feet above the ground surface. Photo shows the home at 14 Sherwood Drive. Photo taken by the author on October 30, 2019.

Table 1. Maximum measured water-surface elevations during flooding of Richwood

Description	Latitude[1] (°N)	Longitude[1] (°W)	River Station[2] (ft)	Elevation (ft)
FM2004 north frontage road near pumping chamber[3]	29.064600	95.431050	85347	15.39
Upstream side of Old Angleton Road bridge[4]	29.068457	95.427204	84585	15.0
Watermark on McKinney fence[5]	29.072679	95.416197	80618	13.42

[1]Measured using Google Earth (WGS 84 coordinate system)
[2]Distance upstream of confluence of Bastrop Bayou with Intracoastal Waterway
[3]Watermark field-surveyed on September 1, 2017 (Grounds, 2019)
[4]Extrapolated from observed stream water-surface elevations on September 1, 2017 (Grounds, 2019)
[5]Surface elevation from StratMap (2018a) combined with watermark measured by author on October 30, 2019

Figure 7b. The fence in the backyard of 12 Sherwood Drive (property of Kevin McKinney) just outside of Richwood shows a watermark below which light-grayish lichens were removed by the flood water. The average watermark along the fence was measured at 24 inches above the ground surface. Photo taken by the author on October 30, 2019.

According to Grounds (2019), the Old Angleton Road bridge corresponded to River Station 84585 feet, a FEMA designation that refers to the distance in feet along Bastrop Bayou upstream from the confluence with the Intracoastal Waterway. The river stations of the other two locations (FM2004 north frontage road and McKinney fence) were then measured as the distance along Bastrop Bayou from the upstream side of the Old Angleton Road bridge to the intersection of a straight line perpendicular to Bastrop Bayou and connecting Bastrop Bayou with the watermark measurement point (see Table 1, Fig. 8). The predictions of the HEC-RAS model were then compared with the measured watermark at the McKinney fence (River Station 80618 feet) by linear interpolation of the predictions made for River Stations 80159 feet and 84155 feet (see Table 1 in this report and Tables 3-4 in Grounds (2019)). The predictions of the HEC-RAS model were compared with the measured watermark at the FM2004 north frontage road (River Station 85347 feet) by linear interpolation of the predictions made for River Stations 84585 feet and 87661 feet (see Table 1 in this report and Tables 3-4 in Grounds (2019)). Tables 3-4 in Grounds (2019) provided the output of the HEC-RAS model for the Old Angleton Road bridge (River Station 84585 feet), so that no interpolation was necessary in this case.

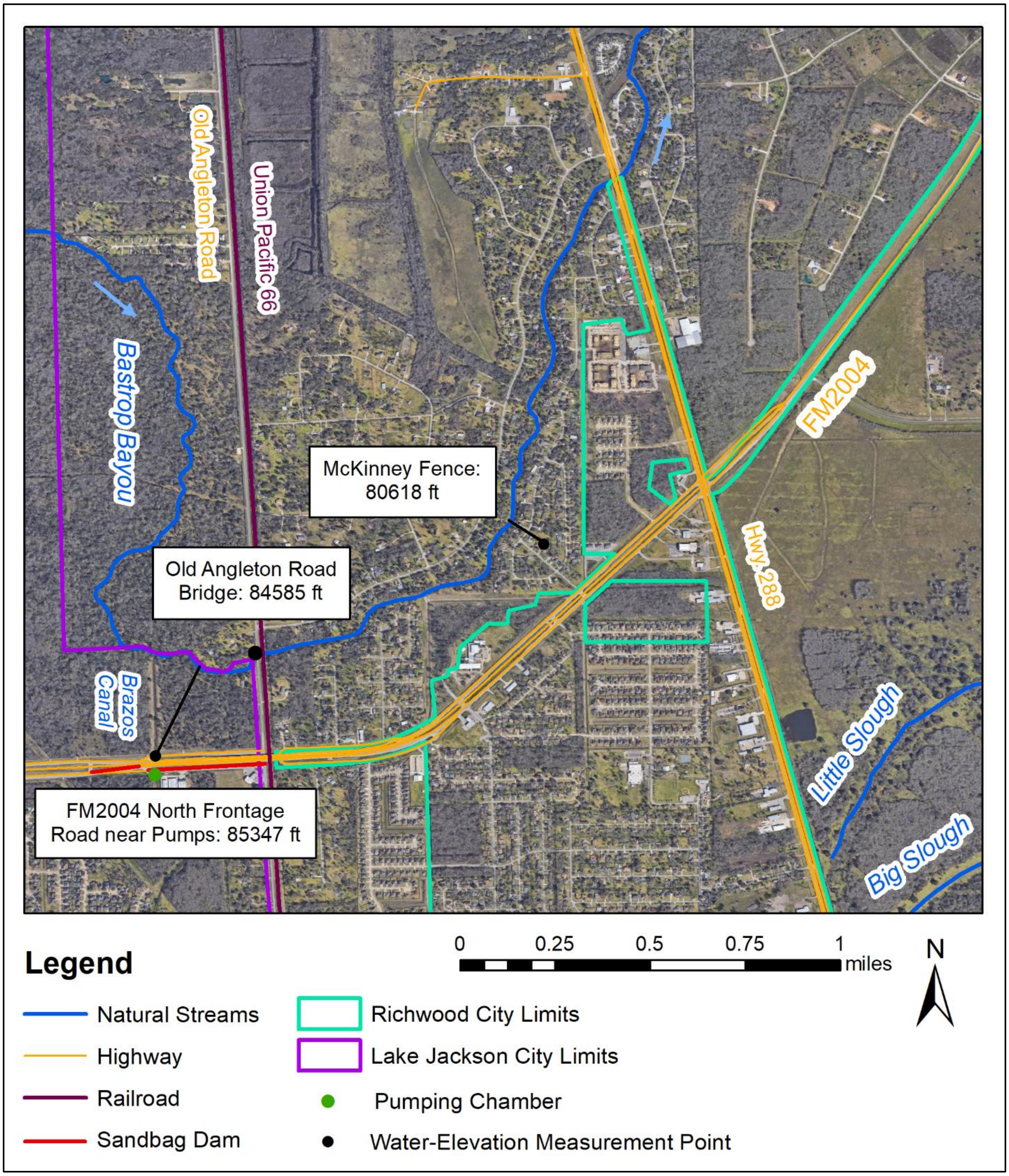

Figure 8. Water elevations were measured at three locations along Bastrop Bayou or in its floodplain (see Table 1). The distances indicate distance upstream from the confluence of Bastrop Bayou and the Intracoastal Waterway. The distance for the upstream side of the Old Angleton Road bridge is given in Grounds (2019). The other distances were measured as the distance along Bastrop Bayou from the upstream side of the Old Angleton Road bridge to the intersection of a straight line perpendicular to Bastrop Bayou and connecting Bastrop Bayou with the water-elevation measurement point. Note that Hwy. 288 is Brazosport Boulevard, not the Nolan Ryan Expressway (compare with Fig. 20).

Grounds (2019) reported additional measurements of water-surface elevations within the pumping chamber itself and at the bridge over Bastrop Bayou on Highway 288, also known as the Nolan Ryan Expressway (not to be confused with the Highway 288 that is also known as Brazosport Boulevard (see Fig. 20)). Water-surface elevations in the pumping chamber were measured from both photos and field-surveying, while water-surface elevations at the Highway 288 bridge were again "extrapolated from observed stream water surface elevations" (Grounds, 2019), which were not reported. Water-surface elevations within the pumping chamber were not compared with predictions of the HEC-RAS model because they were too likely to be dominated by local effects, such as the pumping and the partially-open flap gate. The water-surface elevation at the Nolan Ryan Expressway bridge was also not considered because it is about 29,200 feet farther upstream than the Old Angleton Road bridge (roughly corresponding to River Station 113,785 feet), which is outside of the river reach for which the HEC-RAS model was run (maximum river station 92,200 feet) and far outside of the probable range of influence of the sandbag dam (Grounds, 2019). It is clear that the measurements on the bridge over Bastrop Bayou on Highway 288 refer to the Nolan Ryan Expressway and not Brazosport Boulevard because the measured water-surface elevations (19.8 feet at 2:37 pm on August 31, 19.9 feet at 4:49 pm on August 31, and 20.1 feet at 5:28 am on September 1, 2017) were much higher than at the Old Angleton Road bridge at the same measurement times. (Grounds (2019) also occasionally refers to CR288, which is the same as Old Angleton Road.)

Figure 9. The flood water mostly did not flow directly over the highway FM2004 or the railroad. View looking to the east (compare with veer of FM2004 to the left (northeast) in Fig. 3). It is most likely that the flood water crossed the railroad under the bridge over Bastrop Bayou and crossed FM2004 through culverts that connect the "East Ditch" and "West Ditch" on the north and sides of the highway (see Figs. 3, 10-11). Figure modified from still shot at 4:14 of drone video labeled Before-8 taken on or before September 3, 2017, and provided by Matías J. Adrogué, PLLC.

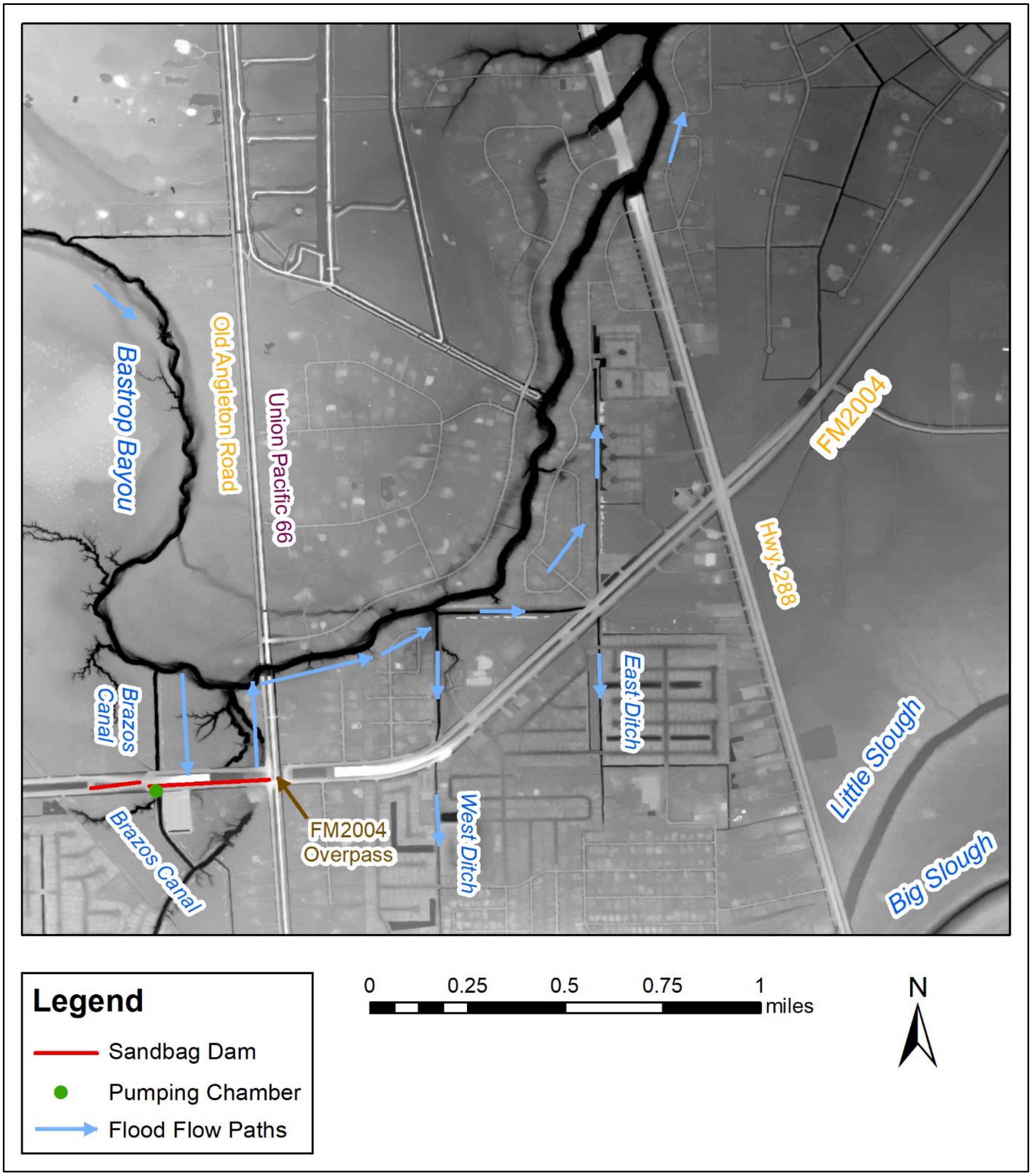

Figure 10. The flood path can be reconstructed by combining drone videos taken during the flooding, post-flooding ground photos, and the 1-meter-pixel Digital Elevation Model (DEM) (StratMap, 2018a-b). The darker shades of gray indicate lower elevations. A notable feature of the DEM is the depression west of Old Angleton Road between Bastrop Bayou and FM2004, where the flood water would have ponded before passing under the bridge over Bastrop Bayou on the southern floodplain of the bayou. In addition, the DEM defines very well the East and West Ditches where the flood would have passed under FM2004 from the north. Finally, the DEM defines the extension of the East Ditch in the northern direction (north of FM2004), which was the most likely pathway for the flood along the southern floodplain of Bastrop Bayou until the flood reentered the bayou. Note that Hwy. 288 is Brazosport Boulevard, not the Nolan Ryan Expressway (compare with Fig. 20).

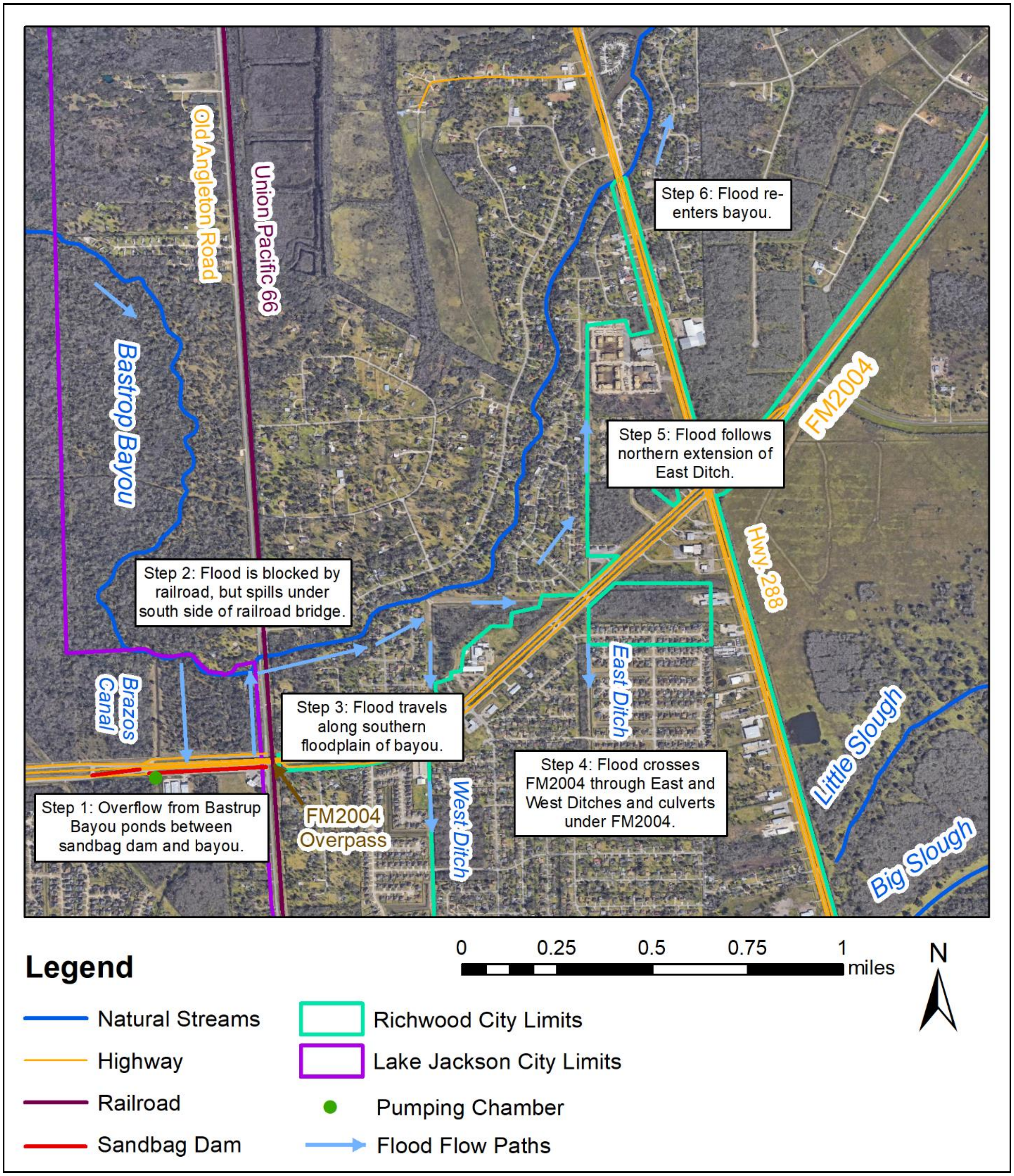

Figure 11. The passage of the flood wave through the city of Richwood can be described by a six-step process. Note that Step 4 (crossing of FM2004) and Step 5 (northward passage of the flood wave along an extension of East Ditch) would have occurred roughly simultaneously. Since the sandbag dam diverted enough water to flood the affected areas to a depth of 46 feet and since the depth of flooding was roughly two feet, about 96% of the diverted water eventually reentered Bastrop Bayou. Note that Hwy. 288 is Brazosport Boulevard, not the Nolan Ryan Expressway (compare with Fig. 20).

RESULTS

Volume of Water Diverted by Sandbag Dam

The interception of water by the sandbag dam was calculated using Eq. (1) with L = 2000 feet (measured from Fig. 3), g = 32.2 ft/s^2, and an assumed H = 1 foot, yielding Q = 4.80 million gpm. As explained above, the sandbag dam was equivalent to a line of pumps that was pumping water across Highway FM2004 at a rate of Q = 4.80 million gpm. Over the four days that the dam existed along the highway, the total volume of water intercepted and redirected by the dam would have been 27.7 billion gallons. This volume of water represents 0.08% of the 33 trillion gallons of water that were dropped from Hurricane Harvey (Pacheco, 2018). Based on the above calculations, the water that was redirected to the north by pumping was negligible compared to the water intercepted by the sandbag dam, especially considering that most of the pumped water was being returned to the south through the partially open flap gate.

Figure 12. During the overflow from Bastrop Bayou, water most likely flowed southward through the culverts underneath the north side (westbound lanes) of FM2004 before ponding against the sandbag dam that was constructed on the south side (eastbound lanes) of FM2004 (see Figs. 3, 4a-c). View looking to the north under the FM2004 overpass over Old Angleton Road (see Fig. 3) from a site slightly west of the site of Fig. 4c. The median strip is visible in the foreground with the FM2004 north frontage road in the middle ground. Note that flood water mostly did not flow across FM2004, but flowed under the highway and ponded in the median strip (see Figs. 4a-b, 5e, 9). Photo taken by the author on October 30, 2019.

Figure 13. It is most likely that the flood water crossed the railroad under the bridge over Bastrop Bayou on the south side (right side of photo) of the bayou (see Figs. 10-11). View looking downstream to the east. Note the stream gage bolted to the bridge. Photo taken by the author on October 30, 2019.

The ability of the total volume of redirected water (27.7 billion gallons) to cause flooding in the city of Richwood and other county areas can be assessed by estimating the surface area that would receive and retain this water. Various polygons can be created that circumscribe the flooded properties (see Fig. 3), but they tend to have surface areas of approximately 80 million square feet (about 1800 acres). Dividing the volume by the affected area results in the conclusion that the affected area could have been flooded to a depth of 46 feet. By contrast, even if the total volume resulting from the maximum pumping rate (2047 gpm) for the 11 days after the flap gate was closed was applied to the area that circumscribes the flooded properties (80 million square feet), the area would have been covered by a non-observable amount of water (less than 0.01 feet). Therefore, this report and the report by the expert witness for the City of Lake Jackson (Grounds, 2019) are in full agreement in determining that the impact of pumping was negligible.

Although sufficient water was diverted to flood the affected areas to a depth of 46 feet, those areas were flooded to an average depth of only two feet (see Figs. 7a-b). Flooding the affected areas to a depth of 46 feet would require that all of the flood water remain in the affected areas with none of the diverted water returning to Bastrop Bayou. However, diverting enough water to flood the affected areas to a depth of 46 feet with an actual flooding depth of two feet means that about 96% of the diverted water eventually flowed back into Bastrop Bayou. The point is that the volume of the diverted water was so great that it is difficult to imagine scenarios under which the diverted water could eventually return to Bastrop Bayou without any residential flooding. For example, even if 99% of the diverted water had returned to Bastrop Bayou, it would still have flooded the affected areas to an average depth of 5.5 inches. Note that, if L = 2500 feet were used instead of L = 2000 feet, the volume of diverted water would be 34.6 billion gallons with a potential depth over the affected area of 58 feet and with 97% of the diverted water returning to Bastrop Bayou.

Figure 14a. Typically, water flows westward (away from the viewer) through the "East Ditch" to Bastrop Bayou (see Fig. 3). However, after diversion by the sandbag dam, water most likely flowed eastward through the same ditch toward FM2004 (see Figs. 10-11).View looking to the southwest. Photo taken by the author on October 30, 2019.

Pathway of Diverted Water

The flood pathway was largely reconstructed using one key observation and one key hydrologic principle. The key observation is that, for the most part, the flood water did not flow over the railroad (Union Pacific 66) and did not flow over Highway FM2004 (see Figs. 3, 9). The key hydrologic principle is that surface water flows from higher to lower elevation of the water surface, and not necessarily from higher to lower elevation of the ground surface (Dingman, 2009). This universal truth is summarized by Dingman (2009), "Of course, river channels almost always slope downstream when measured over distances equal to several widths, but locally the bottom can be horizontal or slope upward. When the local bottom slopes upstream, the slope is said to be adverse…In other words, the water-surface elevation must decrease in the downstream direction if flow is occurring." The reason that water was flowing southward out of Bastrop Bayou was that the water-surface elevation was higher in Bastrop Bayou than it was to the south (for example, on the FM2004 frontage roads). This means that any water that was blocked from flowing farther south by the sandbag dam could not simply be pushed back into Bastrop Bayou, since the water in Bastrop Bayou was at a higher elevation than the diverted flood water. Therefore, much of the discussion of the reconstructed flood path involves the details of the efforts of the diverted flood water to find a pathway back into Bastrop Bayou.

Figure 14b. Typically, water in the "East Ditch" flows from the south side of FM2004, through the culvert under FM2004, and then westward (toward the right in the photo) to Bastrop Bayou (see Fig. 3). However, after diversion by the sandbag dam, water most likely flowed eastward through the same ditch (see Figs. 10-11) and emerged on the south side of FM2004 (opposite side of highway in background of photo). View looking to the south. Photo taken by the author on October 30, 2019.

The first step was the overflow from Bastrop Bayou toward the south and the formation of a pond of water between Bastrop Bayou and the sandbag dam. The flood water arrived at the sandbag dam not by flowing over FM2004, but through culverts that convey water under FM2004 and its north frontage road (see Figs. 10-12). The pond formed because the flood water could not flow farther south, could not return to Bastrop Bayou to the north, and was blocked from flowing to the east by the elevated railroad (see Figs. 9-11). Of course, any passage to the west was inhibited by the naturally rising topography in that direction and the depression (indicated by darker shades of gray) west of Old Angleton Road between Bastrop Bayou and FM2004 (see Fig. 11).

Figure 14c. Typically, water in the "East Ditch" flows northward (toward the viewer) from the south side of FM2004, through the culvert under FM2004, and then westward to Bastrop Bayou (see Fig. 3). View from the south side of FM2004 (note highway in foreground) looking to the south. However, after diversion by the sandbag dam, water most likely flowed eastward through the same ditch, through a culvert under FM2004, and emerged on the south side of FM2004 (see Figs. 10-11). The ditch is close to an interior boundary of the city of Richwood (Richwood on the right side of the photo). Photo taken by the author on October 30, 2019.

The second step was the spillage of the pond to the east under the southern portion of the railroad bridge (see Figs. 10, 11, 13). This flood water would have been confined to the southern portion of the bridge because it could not have entered Bastrop Bayou, which was at a higher water-surface elevation. For the same reason, the third step was the passage of the flood water to the northeast, in the general downstream direction of Bastrop Bayou, but confined to the southern (or southeastern) floodplain of the bayou (see Figs. 10-11). Note that the water-surface elevations reported by Grounds (2019) do not refer to the stream gage that is visible in Fig. 13, since Grounds (2019) reported measurements at the Old Angleton Road bridge, not the railroad bridge (see Fig. 8). (In Fig. 13, the Old Angleton Road bridge would be to the west, behind the viewer). However, observations at the stream gage at the railroad bridge probably are a part of the set of “observed stream water surface elevations” (Grounds, 2019) that were used to calculate the water-surface elevation at the Old Angleton Road bridge.

The fourth step was the interaction of the flood water with the system of ditches that typically convey water from the south side of FM2004, through culverts under FM2004, and to Bastrop Bayou. These ditches are very well-defined by the dark (indicating lower elevations) straight lines in the Lidar-based DEM (see Fig. 10). These ditches do not seem to have official names, and are named in this report as “West Ditch” and “East Ditch” for clarity. The flood water was channeled southward through the West Ditch and eastward through the East Ditch until it crossed FM2004 by flowing through culverts under the highway (see Figs. 10-11, 14a-c, 15a-b). Note that the East Ditch is oriented north-south on the south side of FM2004 (see Figs. 10-11). After crossing under FM2004, the flood water flowed southward through both West Ditch and East Ditch with considerable overtopping of the ditches (see Figs. 10-11).

Figure 15a. Typically, water flows northward (away from the viewer) through the “West Ditch” to Bastrop Bayou (see Fig. 3). However, after diversion by the sandbag dam, water most likely flowed southward through the same ditch toward FM2004 (see Figs. 10-11).View from the north side of FM2004 looking to the north. Photo taken by the author on October 30, 2019.

The fifth step was the northward flow of the remaining flood water (that did not cross FM2004) along the northern extension of East Ditch (see Figs. 10-11). This northward flow probably occurred roughly simultaneously with the flow in the opposite direction to the south side of FM2004 (see Fig. 11). The purpose of this northern extension is perplexing, since, at least at the present time, it does not connect with Bastrop Bayou and does not have any obvious role in promoting effective drainage. The sixth and final step was the eventual reentry of the diverted flood water back into Bastrop Bayou (see Figs. 10-11). This reentry point is not well-defined and was probably relatively diffuse along a long stretch of the bayou.

Figure 15b. Typically, water in the "West Ditch" flows northward (toward the viewer) from the south side of FM2004, through the culvert under FM2004, and then northward to Bastrop Bayou (see Fig. 3). View from the south side of FM2004 looking to the south. However, after diversion by the sandbag dam, water most likely flowed southward through the same ditch, through a culvert under FM2004, and emerged on the south side of FM2004 (see Figs. 10-11). The ditch is close to the boundary of the city of Richwood (Richwood on the left side of the photo). Photo taken by the author on October 30, 2019.

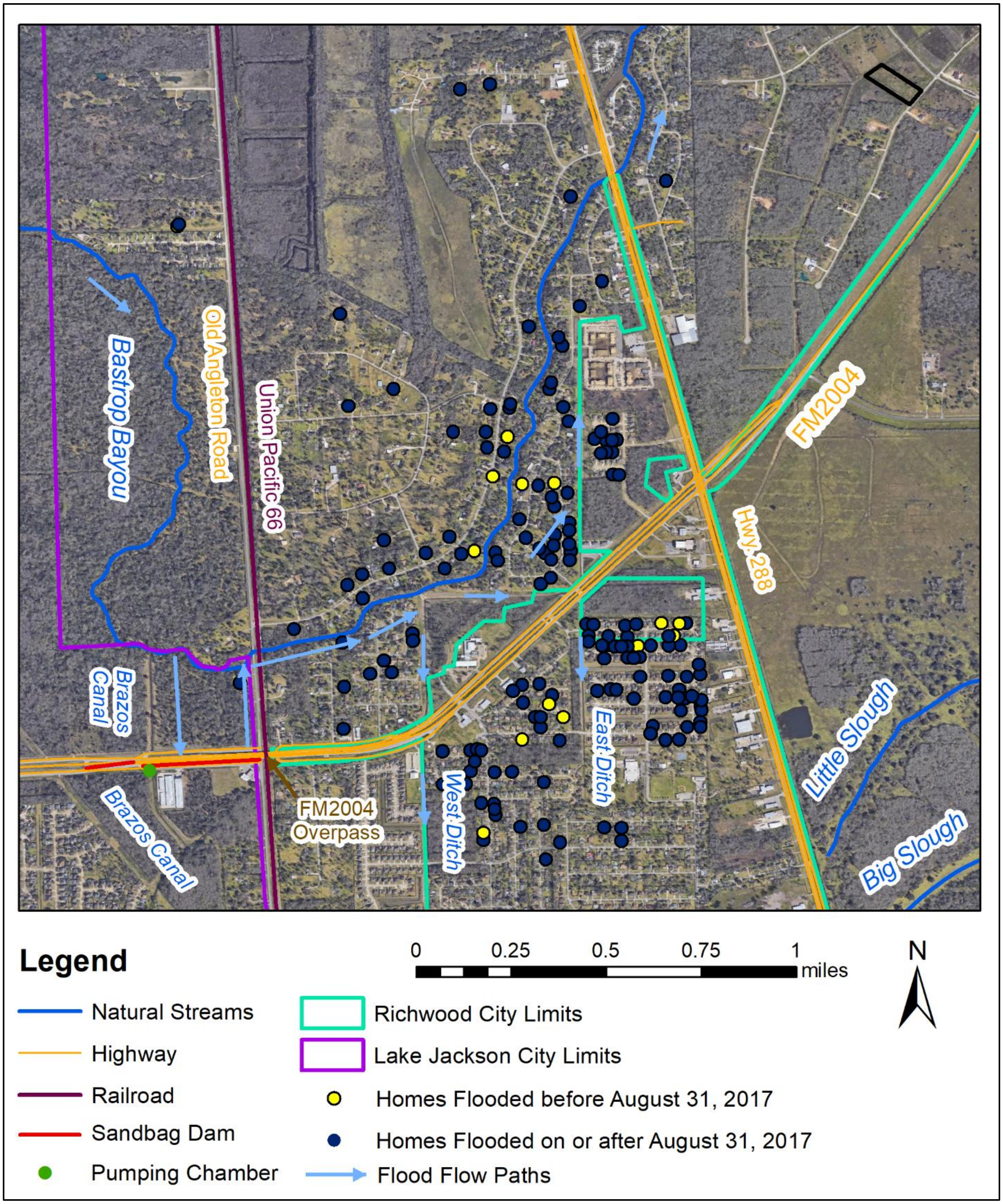

Figure 16. Out of 190 respondents who reported home flooding times, 89% were flooded on or after August 31, 2017 (the first day of sandbagging), while 78% were flooded on either August 31 or September 1. The median time of flooding was midnight between August 31 and September 1. The homes that reported flooding prior to the placement of the sandbag dam are almost entirely (81%) located south of Bastrop Bayou. Without the intervention of a sandbag dam that forced water to flow along the southern floodplain of Bastrop Bayou, the flooding would have progressed in the downstream direction and would have been more symmetric about the bayou. Note that Hwy. 288 is Brazosport Boulevard, not the Nolan Ryan Expressway (compare with Fig. 20).

Comparison of Models with Flooding Times

The timing of flooding as reported by the residents of the flooded properties was examined for its consistency with the timing of the placement of the sandbag dam, with the predicted flow paths of the redirected water (see Figs. 10-11), and with the alternative flooding model (overflow from the Brazos River) of Grounds (2019). Out of 190 respondents who reported home flooding times, 89% were flooded on or after August 31 (the first day of sandbagging), while 78% were flooded on either August 31 or September 1 (see Fig. 16). The median time of home flooding was midnight between August 31 and September 1. The homes that reported flooding prior to the placement of the sandbag dam were almost entirely (81%) located south of Bastrop Bayou (see Fig. 16). The consideration of any time intervals finer than a two-way division (such as, before August 31, and on or after August 31) did not reveal any additional insight, nor did the added consideration of the earlier flooding times of streets and yards. Based on the two-way division, the adjustments described earlier (which adjusted only times and not days) were not relevant.

The most important consideration is that almost all (89%) of the flooding occurred after the placement of the sandbag dam. The temporal pattern of flooding is difficult to reconcile with the alternative flooding model of Grounds (2019), according to which, an overflow of the Brazos River crossed Oyster Creek and entered the watershed of Bastrop Bayou (see Fig. 2), considerably upstream from the flooded properties (compare Fig. 2 with Figs. 3 and 16). If those events had occurred, the flooding would have progressed in the downstream direction and would have been more symmetric about Bastrop Bayou. In addition, in accordance with the alternative flooding model of Grounds (2019), the occurrence of flooding subsequent to the placement of the dam would have been only a coincidence. In fact, the spatial and temporal pattern of flooding is much more consistent with the flood path reconstructed in this report, in which a flood wave is initiated with the advent of sandbagging, followed by flow along the southern floodplain of Bastrop Bayou with eventual reentry into the bayou (see Fig. 16).

Comparison of Measured and Predicted Watermarks and Water-Surface Elevations

In comparing the predictions of the HEC-RAS model used by Grounds (2019) with the measured watermarks and water-surface elevations, it is important to note that Grounds (2019) used the HEC-RAS software in its steady-state setting. Steady-state flow means that, at a given point, the water velocity (both its magnitude and direction) is not changing with time, nor is the water-surface elevation changing with time (Dingman, 2009). In the case of river flow, this would mean that no water is flowing either into or out of the river, which would cause water-surface elevations in the river to be either rising or falling with time. In other words, all flow in the floodplain must be parallel to the river and the water-surface elevation must be constant along any line perpendicular to the river. This steady-state assumption is what makes it possible to equate a measured water-surface elevation on the floodplain with the water-surface elevation in the river at the equivalent river station (assigned by connecting a line perpendicular to the river with the measurement location on the floodplain; see Fig. 8). Although Grounds (2019) never stated that he used the steady-state setting, the assumption of steady-state flow is clear because all predictions (discharges and water-surface elevations) were stated only as constant numbers with no changes through time.

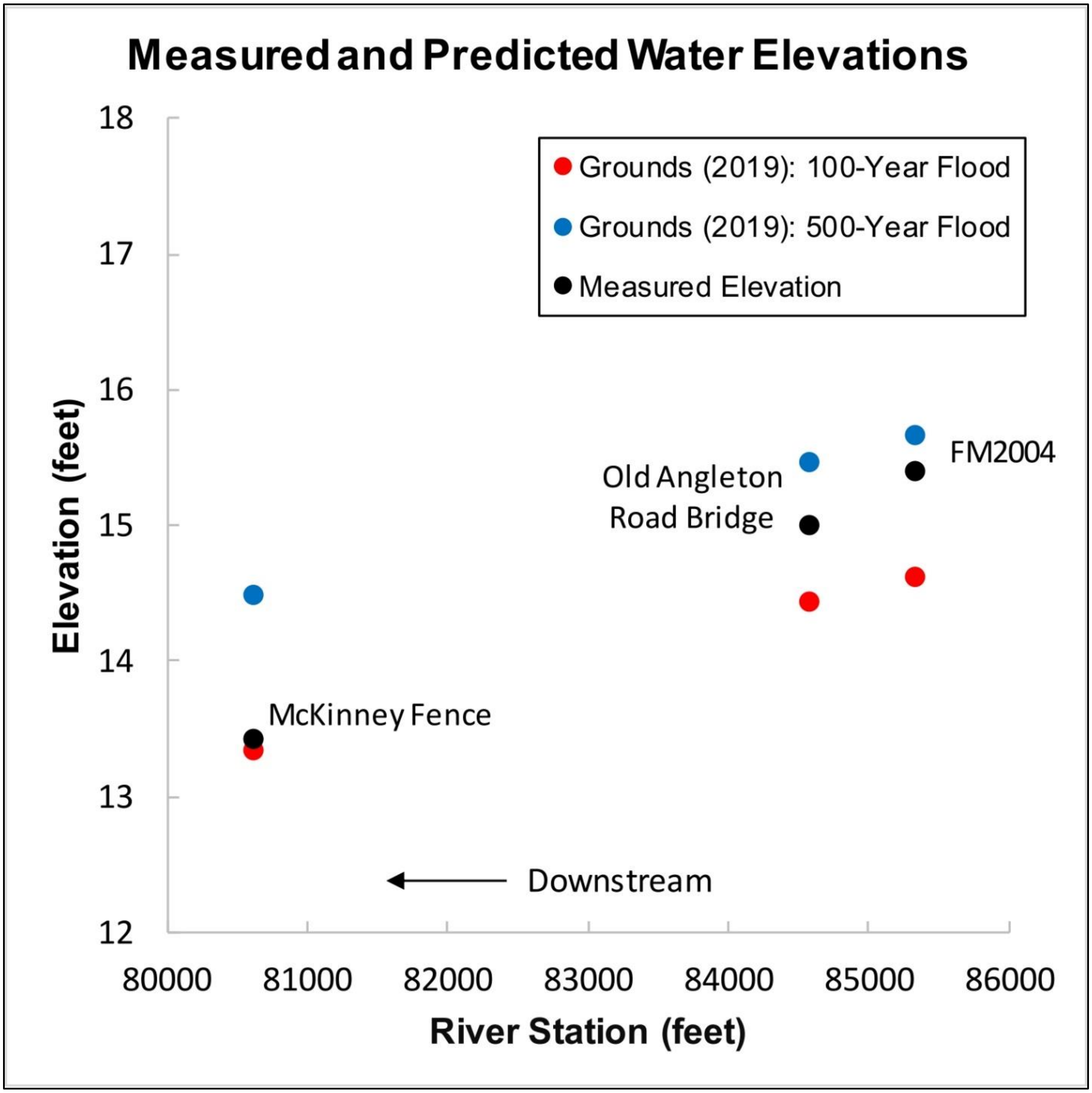

Figure 17. Water-surface elevations measured at three locations (see Table 1 and Fig. 16) were compared with the predictions of Grounds (2019) for combining pumping and a sandbag dam with the 100-year flood and the 500-year flood. At the two upstream sites, the measurements were between the predictions for the 100-year and 500-year floods (closer to the 500-year flood). However, at the McKinney fence, the measured elevation (13.42 feet) was nearly equal to the predicted elevation for only the 100-year flood (13.33 feet). Although the measured elevations are not consistent with the model of Grounds (2019), they are qualitatively consistent with the flood path that was reconstructed in this report (see Figs. 10-11). The McKinney property was not flooded by a simple overflow of Bastrop Bayou, but by a flood wave traveling along the southern floodplain of the bayou (see Figs. 9-10). This flood wave should have had a lower water-surface elevation than the bayou.

The measured watermarks and water-surface elevations are generally not consistent with the HEC-RAS model (Grounds, 2019) because they show a much steeper drop in the water surface along Bastrop Bayou than was predicted by the model (see Fig. 17). At the farthest upstream site (FM2004 north frontage road), the measured water-surface elevation was 15.39

feet, while the HEC-RAS model predicted an elevation of 14.61 feet for a 100-year flood and 15.65 feet for a 500-year flood, so that the measurement was 75% of the way from a 100-year flood to a 500-year flood (see Fig. 17). At the next site downstream (Old Angleton Road bridge), the measured water-surface elevation was 15.0 feet, while the HEC-RAS model predicted an elevation of 14.43 feet for a 100-year flood and 15.45 feet for a 500-year flood, so that the measurement was 56% of the way from a 100-year to a 500-year flood (see Fig. 17). Finally, at the McKinney fence, the measured watermark elevation was 13.42 feet, while the HEC-RAS model predicted an elevation of 13.33 feet for a 100-year flood and 14.47 feet for a 500-year flood, so that the measurement was 8% of the way from a 100-year flood to a 500-year flood, or essentially equal to what would occur during a 100-year flood (see Fig. 17).

Figure 18. The Brazos River is well-known for its muddy water. This muddy water should have been visible in Richwood if the flooding in Richwood had resulted from an overflow of the Brazos River, as claimed by Grounds (2019). Photo from National Weather Service (2019).

The flood path that was reconstructed in this report is qualitatively consistent with the measured watermarks and water-surface elevations. In this regard, it must be emphasized that the reconstructed flood path is not a steady-state model, but the very opposite, because it shows a flood wave progressing through time and space from the sandbag dam to eventual reintegration with Bastrop Bayou (see Figs. 10-11). According to the reconstructed flood path, the water-surface elevation at the McKinney fence (see Fig. 8) should have been lower than the water-surface elevation at the corresponding point in Bastrop Bayou (as measured along a line perpendicular to Bastrop Bayou). At the location of the McKinney fence, the flood wave was still largely blocked from reentering Bastrop Bayou due to the higher water level in the bayou (compare Fig. 8 with Figs. 10-11). Based on Fig. 17, the water level in Bastrop Bayou could have been more or less a foot higher than at the McKinney fence. The reconstructed flood path does not make a quantitative prediction of the water-surface elevation at the McKinney fence, but assures only a higher water level in Bastrop Bayou. The only real quantitative prediction of the model of this report is the volume of water available for flooding (which is not provided by the HEC-RAS model (Grounds, 2019)).

Figure 19a. Clear water is evident in the flooding of a garage and driveway in Richwood. The clarity of the water is indicated in the ability to see the surface of the garage floor and driveway. The clarity of the water draws into question the claim by Grounds (2019) that the flooding of Richwood resulted from the overflow of the Brazos River (compare with muddy water of Brazos River in Fig. 18). Still shot at 1:21 of video entitled "Richwood Flooding Harvey" produced by abc13 Eyewitness News (Barragan, 2017).

Evaluation of Origin of Flood in Overflow of Brazos River

The alternative model of Grounds (2019), that the origin of the flood was in an overflow of the Brazos River near Harris Reservoir (see Fig. 2), makes two testable predictions. The first prediction is that extensive flooding should have occurred not only in the city of Richwood and adjacent county areas, but all along the pathway between Harris Reservoir and Richwood (see Fig. 2). If the overflow from the Brazos River had crossed Oyster Creek to enter into the watershed of Bastrop Bayou, then Oyster Creek should also have flooded. In other words, residential flooding should have occurred in all of the downstream communities of Oyster Creek, including Holiday Lakes, Bailey's Prairie and Lake Jackson itself (see Fig. 2). Residential flooding should even have occurred in the western and southwestern portions of Angleton, depending upon where the flood wave would have entered the watershed of Bastrop Bayou (see

Fig. 2). The fact that this spatial and temporal pattern of residential flooding along Oyster Creek has not been documented casts doubt upon the alternative flooding model.

Figure 19b. Clear water is evident in the flooding of the streets and lawns in Richwood. The clarity of the water is indicated in the ability to see the driveway surfaces and the lawn grass. The clarity of the water draws into question the claim by Grounds (2019) that the flooding of Richwood resulted from the overflow of the Brazos River (compare with muddy water of Brazos River in Fig. 18). Still shot of drone video taken between August 30 and September 1, 2017, and provided by Matías J. Adrogué, PLLC.

The alternative model of the origin of the flood in an overflow of the Brazos River also makes predictions regarding the appearance of the flood water. The Brazos River is well-known for its muddy water, which becomes even muddier at flood stage (see Fig. 18). If the Brazos River had been the source of flooding, this muddy water would be evident throughout the numerous drone videos and ground photos that were available to the author. By contrast, the flood water was remarkably clear, which was evidenced in the ability to see through the flood water to lawns, streets and driveway surfaces (see Figs. 19a-c). It is interesting that the Northwood neighborhood of Lake Jackson (north of FM2004; see Fig. 20) was also flooded and drone videos again show the ability to see through the remarkably clear flood water to lawns, streets and driveways (see Fig. 21). The Northwood neighborhood may have been flooded by either Bastrop Bayou from the northeast or Oyster Creek from the southeast or both (see Fig. 20). However, based on the clear flood water, neither an overflow from Bastrop Bayou nor an overflow from Oyster Creek could have originated in an overflow of the Brazos River. The failure of the alternative model to correctly predict either the flood pathway or the appearance of the flood water makes it very unlikely that the flooding of Richwood and surrounding county areas originated in an overflow of the Brazos River.

Figure 19c. Clear water is evident in the flooding of the streets and lawns in Richwood. The clarity of the water is indicated in the ability to see the street surfaces. The clarity of the water draws into question the claim by Grounds (2019) that the flooding of Richwood resulted from the overflow of the Brazos River (compare with muddy water of Brazos River in Fig. 18). Photo taken by Lance Wallace on September 3, 2017.

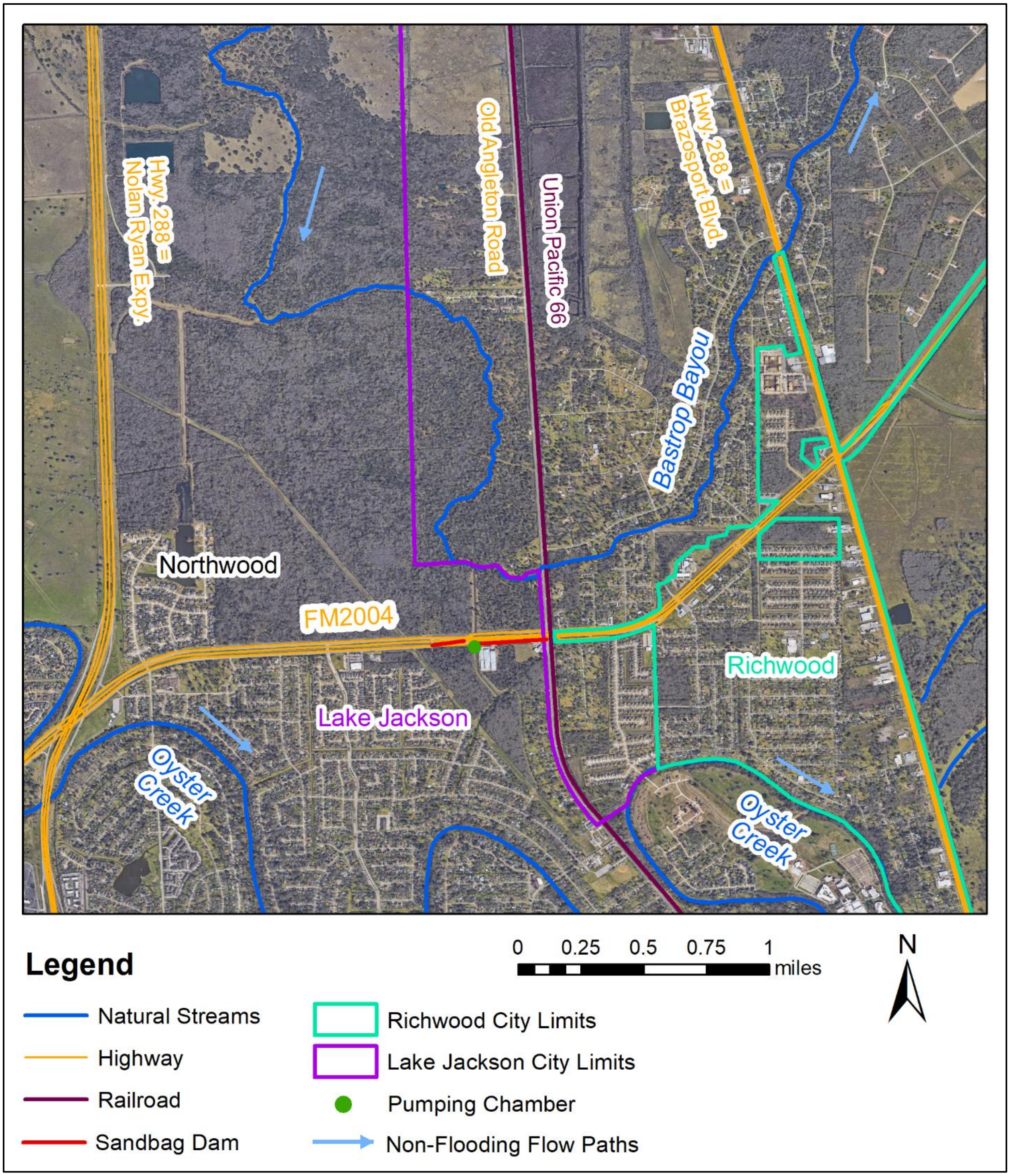

Figure 20. The Northwood neighborhood of Lake Jackson was also flooded by clear water (see Fig. 21), just like the city of Richwood (see Figs. 19a-c). In light of the well-known muddy water of the Brazos River (see Fig. 18), the Northwood neighborhood was either flooded by an overflow of Oyster Creek or Bastrop Bayou, in either case, without the input of flood water from the Brazos River.

Figure 21. Clear water is evident in the flooding of the streets and lawns in the Northwood neighborhood of Lake Jackson (see Fig. 14). The clarity of the water is indicated in the ability to see the street and driveway surfaces, as well as the lawn grass. The clarity of the water draws into question the claim by Grounds (2019) that the flooding of either Richwood or Lake Jackson resulted from the overflow of the Brazos River (compare with muddy water of the Brazos River in Fig. 18). Still shot at 2:24 of drone video entitled "Northwood Flooding during Harvey in Lake Jackson, TX" (Tlath88, 2018).

DISCUSSION

Failure of HEC-RAS Model

The obvious question at this point is: Why did this report and the report by the expert witness for the City of Lake Jackson (Grounds, 2019) arrive at different conclusions regarding the cause of the flooding of Richwood and surrounding county areas? It has already been mentioned that the author of this report had access to information that was not available to Grounds (2019), including the new Lidar data, flooding times reported by residents, ground photos taken during a site visit, and watermarks measured in the area of the flooded properties. However, the HEC-RAS software, which was the basis for the conclusions of Grounds (2019) is widely used by governmental agencies throughout the U.S. Therefore, the real question is: In this case, why did the HEC-RAS software yield the wrong answers (predictions that were inconsistent with observations)? Software output can be no better than the input and the settings. There is never a guarantee that the input and settings are correct. Therefore, any use of hydrologic software includes the necessity to compare the predictions with observations (called calibration or verification of the model). Grounds (2019) did not indicate that anything had been done to verify the output of the HEC-RAS software. However, an attempt at verification would have revealed that something had been done wrong.

As stated by Grounds (2019), all of the inputs for the HEC-RAS model were taken from FEMA (2018), including topographic data, the discharges of rare events (such as the 100-year and the 500-year flood), and the relevant streambed characteristics (such as the Manning roughness coefficients). It is worth considering each of the inputs for sources of error or uncertainty. The topographic database did not include the most recent Lidar data (StratMap, 2018a-b), with the next most recent Lidar data having been collected 11 years prior to the flooding in Richwood (FEMA, 2006). The discharges of rare events are typically predicted based on decades of automatically-recorded stream discharge measurements at, for example, 15-minute intervals. Even so, there can be considerable uncertainty in the prediction of the discharge of a 500-year flood based on 30 years of stream discharge measurements. By contrast, I have not found any record of any stream discharge measurements on Bastrop Bayou. Although there is a stream gage at the railroad bridge across Bastrop Bayou (see Fig. 13), this gage has no mechanism for automatic recording. I have found no consistent record of manual measurements and certainly no development of rating curves that could be used to convert gage heights to stream discharges. (A rating curve would typically be developed by carrying out about 30 simultaneous manual measurements of stream discharges and gage heights over a wide range of discharges.) Another stream gage with automatic recording was installed on Bastrop Bayou under the Old Angleton Road bridge (see Fig. 3) only on August 13, 2019, and the rating curve is still under development (USGS, 2019). On the above basis, although there are empirical methods for estimating the magnitudes of extreme events on streams with no discharge record (called an ungaged steam), these estimates should be regarded as highly uncertain.

The greatest source of error could have been the setting in the HEC-RAS model that determined that a steady-state flow solution would be calculated. The steady-state assumption is equivalent to calculating the flow situation that would result once Bastrop Bayou and its floodplain had reached an equilibrium in response to changes in discharge and topography (the sandbag dam). In other words, the HEC-RAS software calculated the equilibrium flow situation that would eventually exist if a 100- to 500-year flood occurred and a 24-inch high, 2000-foot sandbag dam were constructed, and if those changes then continued indefinitely. Eventually, Bastrop Bayou would simply widen to engulf much of its current floodplain with all of the flow parallel to the river banks. The expert witness for the City of Lake Jackson calculated the amount by which that equilibrium river would differ if the topographic equivalent of the sandbag dam did or did not exist, and found that the difference would be negligible. That conclusion could be correct, but it is very different from considering the sudden (time-dependent) appearance of a sandbag dam in response to an overflow of Bastrop Bayou and the resulting diversion of water and the creation of a flood wave that progresses through space and time.

In summary, there are three possible sources of error and it is not obvious which of those sources was the most significant. However, it is never appropriate to trust software output without comparing it with observations. When predictions do not adequately match observations, it is necessary to reconsider the input to the software, the settings of the software, and even the choice of software. These requirements would apply to both the quantitative output of the HEC-RAS model and the qualitative output of the model that assigned the origin of flooding to an overflow of the Brazos River.

Could Flooding of Richwood have been Predicted?

It is now appropriate to consider the question as to whether City of Lake Jackson personnel could have predicted that their placement of a sandbag dam would have resulted in the flooding of the city of Richwood and adjacent county areas. According to Grounds (2019), the water-elevation difference across the flap gate was apparent on August 28, 2017. At that point, the volume of water that would be diverted by constructing a sandbag dam across FM2004 could have been predicted by the City Engineer for the City of Lake Jackson, or by other personnel with similar engineering background. On that basis, the impact of the sandbag dam could have been predicted before the dam was constructed on August 31.

The real answer to the question is that constructing a dam along a highway in response to flooding in an urban area is rarely a good idea. Flood water cannot simply be pushed back in the direction from which it came; it can only be diverted in some other downstream direction. The city of Richwood is downstream from the city of Lake Jackson, so that it should have been clear that, somehow, Richwood was going to become the host for the diverted flood water. As opposed to the ad hoc construction of urban dams, it is necessary to construct the necessary hydraulic infrastructure for the intentional diversion of flood water, so that nobody is saved from flooding at someone else's expense. I would be happy to assist with this type of design or planning, but this is far out of the scope of the present report.

Answers to Objectives

Based upon the preceding discussion, the answers to the questions that were the objectives of this report can be stated as follows:

1) The pumping, more likely than not, did not cause the flooding of Richwood and other county areas outside of Lake Jackson.
2) The placement of the sandbag dam, more likely than not, did cause the flooding of Richwood and other county areas outside of Lake Jackson.
3) The combination of the sandbag dam and the pumping, more likely than not, did cause the flooding of Richwood and other county areas outside of Lake Jackson, although the added impact of pumping was negligible.
4) The impacts of placement of the sandbag dam could have been predicted at the time.

CONCLUSIONS

The conclusions of this report can be summarized as follows:

1) The diversion by the sandbag dam was equivalent to a row of pumps that would have been pumping water from south to north at 4.8 million gallons per minute (gpm), for a total of 27.7 billion gallons of water for the four days of sandbagging, which would have been enough water to cover the flood-affected area to a depth of 46 feet.
2) The 2018 Lidar data, drone videos taken during the flooding, and post-flooding ground photos were used to reconstruct the path of the flood wave into the neighboring city of Richwood and eventually back into Bastrop Bayou.
3) Based on watermarks on houses and fences, Richwood was flooded to an average depth of two feet, so that about 96% of the diverted water reentered the bayou after passing through Richwood.

4) The home flooding times reported by the residents are consistent with the reconstructed flood path, and not with a simple overflow of Bastrop Bayou without the intervention of a sandbag dam.
5) Measured watermarks and water-surface elevations were also consistent with the reconstructed flood path, but not with the output of a HEC-RAS model that was used by the expert witness for Lake Jackson.
6) The failure of the HEC-RAS model was probably caused by a combination of outdated topography, lack of knowledge of the magnitudes of extreme events on Bastrop Bayou (an ungaged stream), and the assumption of steady-state flow (as opposed to a time-progressive flood).
7) The alternative flooding model proposed by the expert witness for Lake Jackson, that the origin of the flood was an overflow of the Brazos River that crossed Oyster Creek and entered the watershed of Bastrop Bayou, was inconsistent with the lack of flooding of municipalities along Oyster Creek, including Holiday Lakes, Bailey's Prairie, and Lake Jackson itself.
8) An origin of the flood in the Brazos River, which is well-known for its muddy water, is inconsistent with the very clear flood water in Richwood that is evident in ground photos and drone videos.
9) Based on the preceding points, the sandbag dam, but not the pumping, was certainly responsible for the flooding in the city of Richwood and other county areas.

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