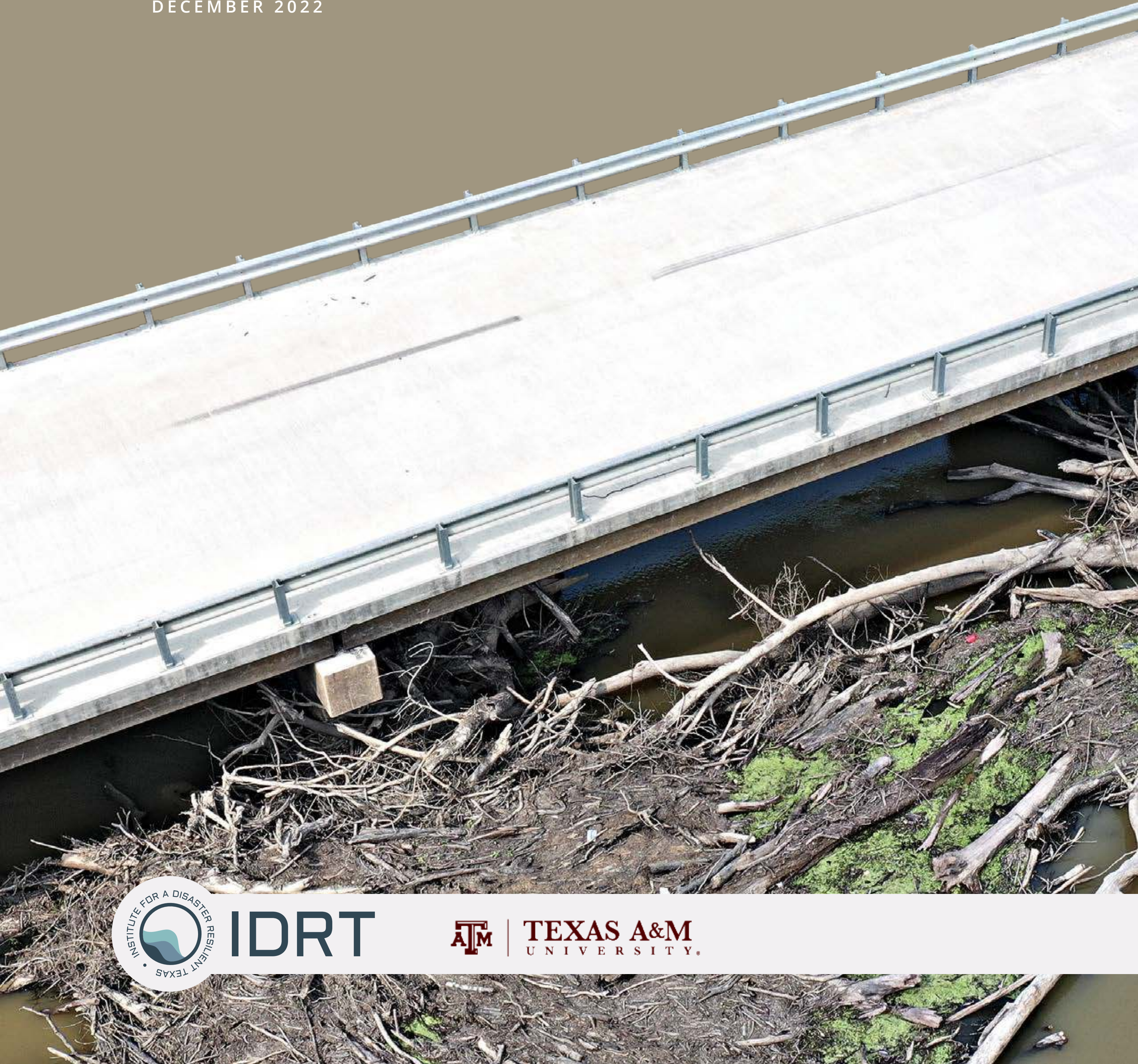
NAVASOTA RIVER
FLOODING PROJECT

REPORT FINDINGS & RECOMMENDATIONS

DECEMBER 2022



INSTITUTE FOR A DISASTER RESILIENT TEXAS
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EXECUTIVE SUMMARY

From 2021 to 2022, the Texas A&M Institute for a Disaster Resilient Texas conducted a year-long, multidisciplinary study to investigate potential causes of increased flooding along the Navasota River south of Lake Limestone. Guided by the interests of local stakeholders, researchers analyzed the potential impacts of the Sterling C. Robertson dam on Lake Limestone on downstream flooding. The study identified multiple drivers of flooding acting at a watershed scale.

The results of the analysis revealed that the Lake Limestone dam is not causing increased flooding downstream. Instead, the primary driver of flooding is rainfall, particularly high intensity rainfall events, compounded by increased development, debris blockages, and straightening of the river over time. Nevertheless, the experiences of the landowners who provided input for this study underscore realities of flood impacts that merit additional attention. More data collection, analyses, and localized investigations should continue to be pursued by local and regional jurisdictions and planning groups.

The area for this study is the Navasota River watershed, as seen in Figure 1, focused on the area south of Lake Limestone to the city of Navasota at the confluence of the Navasota River and the Brazos River.

FIGURE 1: NAVASOTA RIVER WATERSHED

Note: The Navasota River starts in Mount Calm, Texas and flows southeast for 125 miles before reaching the Brazos River. The river has been dammed at six locations, including to create Lake Limestone in 1978.[1]

KEY FINDINGS

DECEMBER 2022

A NATURALLY FLOOD-PRONE REGION

Much of the localized flooding along the Navasota River in the study area is driven by the river's natural tendency to flood due to climate, soils with slow infiltration that produce high runoff during rainfall events, and broad floodplains. For example, nearly three-quarters of the watershed consists of soils with slow infiltration, much of it located in the southern portion of the watershed.[2]

THE UNDERLYING DRIVERS OF INCREASING FLOOD RISK

Several trends contribute to the increases in flooding and associated adverse impacts within the watershed.

Increasing Rainfall

The primary driver of flooding is rainfall, particularly high intensity rainfall events that can overwhelm the natural drainage capacity of the soil. Within the Navasota River watershed, rainfall trends have been increasing over time, with 2015 being one of the wettest years on record. With more rainfall comes increasing streamflow and risk of flooding of adjacent land due to river overbanking.

Increasing Development & Impervious Surfaces

Since 2001, the Navasota River watershed has added about 19,000 acres of new development, much of it in the Bryan-College Station area. Although measures such as requirements for retention ponds may mitigate this impact, previous studies have shown that flood risk can increase despite such efforts.[3]

Riverine Debris

Flood hazard is often considerably increased whenever large amounts of instream debris prevent or impede the flow of water.[4] By conducting unmanned aerial vehicle (drone) flights around five bridge crossings, this study identified one bridge with a major blockage (Long Trussell Road or County Road 162). The other four bridges flown had less immediately identifiable blockages at the bridge site or could not be assessed due to heavy tree canopy. However, several areas of debris could be identified in the immediate upstream/downstream vicinity of bridges that could contribute to future blockages.

A Straightening River Path

By analyzing aerial imagery dating back to the 1970s, the study found that the Navasota River (from State Highway OSR to the Brazos confluence) has significantly straightened over time, resulting in a river that is roughly 2.7 miles shorter than it was in 1972. This straightening and shortening of the river has likely resulted in faster moving water, increased erosion and debris transport, and increased downstream flood risk.[5]

KEY FINDINGS

THE IMPACT OF THE DAM ON DOWNSTREAM FLOODING

Lake Limestone is a water supply reservoir owned and operated by the Brazos River Authority (BRA) to meet regional water demands. As such, it is designed to stay as full as possible and pass through any excess water it receives from rainfall events downstream (known as "run-of-the-river operations"). While water supply reservoirs are not designed for flood control, they can provide some flood mitigation benefit by reducing peak flows during rainfall events.[6] However, some landowners downstream of Lake Limestone are concerned that releases from the reservoir have been contributing to increases in flooding and changing flooding patterns since the dam's construction.

This study analyzed two past rainfall events to evaluate the potential impacts of the dam on downstream flooding— including the timing (how soon floodwaters arrive), flow (the speed and volume of the floodwater moving in the river), depth (how deep the floodwaters get), and duration (how long it takes floodwater to recede). Study researchers compared these two rainfall events to a modeled scenario of what flooding would have looked like if there had been no dam. (The study did not explore the impact of potential changes to the purpose, design, or operations of the dam.)

KEY FINDINGS

RIVER MANAGEMENT AND FLOOD RISK CONCERNS

The study included a survey, focus group, and interviews with a total of 35 landowners along the Navasota River. The BRA's management of the Lake Limestone dam dominated these stakeholders' concerns regarding the effect of flooding on their properties. However, landowners acknowledged increased development in the region and debris in the river as contributing factors. Overall, study participants indicated that the roles and responsibilities of various government agencies involved in managing the Navasota River - and flooding, in general - are not clear to landowners. Many stakeholders wanted to know who is responsible for dredging and clean-up of the Navasota River, including clearing debris around bridges. The study also revealed polarization in stakeholders' views of the BRA. While many were dissatisfied with the BRA's overall role in flood protection, most were satisfied with BRA's dam release notifications as it has helped them plan for flooding on their properties.

LIMITATIONS

This study analyzed available watershed-level data and made conclusions about the primary drivers of flooding in the region with reasonable confidence. However, data limitations required some generalizations and did not allow for more nuanced analysis of localized, property-specific (parcel-level) concerns expressed by some stakeholders. Addressing data gaps identified by this study's researchers would improve future research and help identify and optimize flood reduction strategies in the region. In particular, the strategic placement of more rain and stream gauges in the lower portion of the watershed would help improve the accuracy of both rainfall and streamflow estimates.

This study concluded that the dam has not exacerbated flooding downstream in any noticeable way. The dam's most notable effect was on the timing of when the flooding occurred. The analysis found that the Lake Limestone dam delays when flooding occurs and generally, the closer someone is to the dam, the greater the lag time will be. The analysis did not find significant differences between extent, depth, and duration of flooding of the two modeled rainfall events compared to the "no-dam" scenario.

KEY RECOMMENDATIONS

DECEMBER 2022

SUPPORT THE REGION 8, LOWER BRAZOS REGIONAL FLOOD PLANNING DRAFT PLAN

This study strongly supports the draft recommendations of the Region 8 Lower Brazos Reginal Flood Planning Group. However, in future planning cycles, more outreach should be performed among potential project sponsors in the Navasota River watershed to ensure a wider range of projects are included in the regional plan.

CLARIFY DEBRIS MANAGEMENT PROGRAMS AND FUNDING

Future regional flood planning cycles should focus on clarifying roles, responsibilities, and funding sources for debris removal programs for mitigation purposes. The Texas Department of Transportation and local infrastructure agencies should be better integrated into regional flood planning and more directly contribute information about debris removal around bridges to support future mitigation planning.

IMPROVE STAKEHOLDER COMMUNICATIONS DOWNSTREAM OF LAKE LIMESTONE

The BRA should develop communications specific to their role and those of other entities along the river, especially regarding debris removal, and conduct additional outreach with stakeholders below Lake Limestone to continue improving relationships in the region.

EMBRACE MULTI-PRONGED, WATERSHED-LEVEL FLOOD RESILIENCE STRATEGIES

The flood resilience framework adopted by the Commission to Rebuild Texas following Hurricane Harvey should continue to be implemented through the state's regional flood planning process as well as through local mitigation activities. The Commission's framework organizes approaches to resilient flood mitigation around concepts of avoiding, resisting, accommodating, and communicating flood risk.[7]

COLLECT ADDITIONAL DATA & CONDUCT STUDIES TO MONITOR THE NAVASOTA RIVER OVER TIME

The BRA, working with other local jurisdictions and the U.S. Geological Survey (USGS), should fund the placement of additional gauges downstream of Lake Limestone to better monitor localized flooding concerns. A range of other identified data gaps and additional studies should also be addressed to support more accurate ongoing evaluation of flooding experiences and concerns.

FURTHER DEVELOP MULTIDISCIPLINARY FLOOD EVALUATION METHODS

This study piloted a rapid, multidisciplinary approach to investigating flooding concerns that serves as an example for diagnosing and mitigating negative flood impacts in the future. Research innovations include: the use of drones to collect data, coordination of multiple modeling techniques, integration of social science methods to rapidly assess localized flooding concerns, and the fusion of these different data streams to form a comprehensive picture of flood impacts along the Navasota River. The Institute and partner organizations should pursue these types of problem-solving research projects in the future.

ENDNOTES

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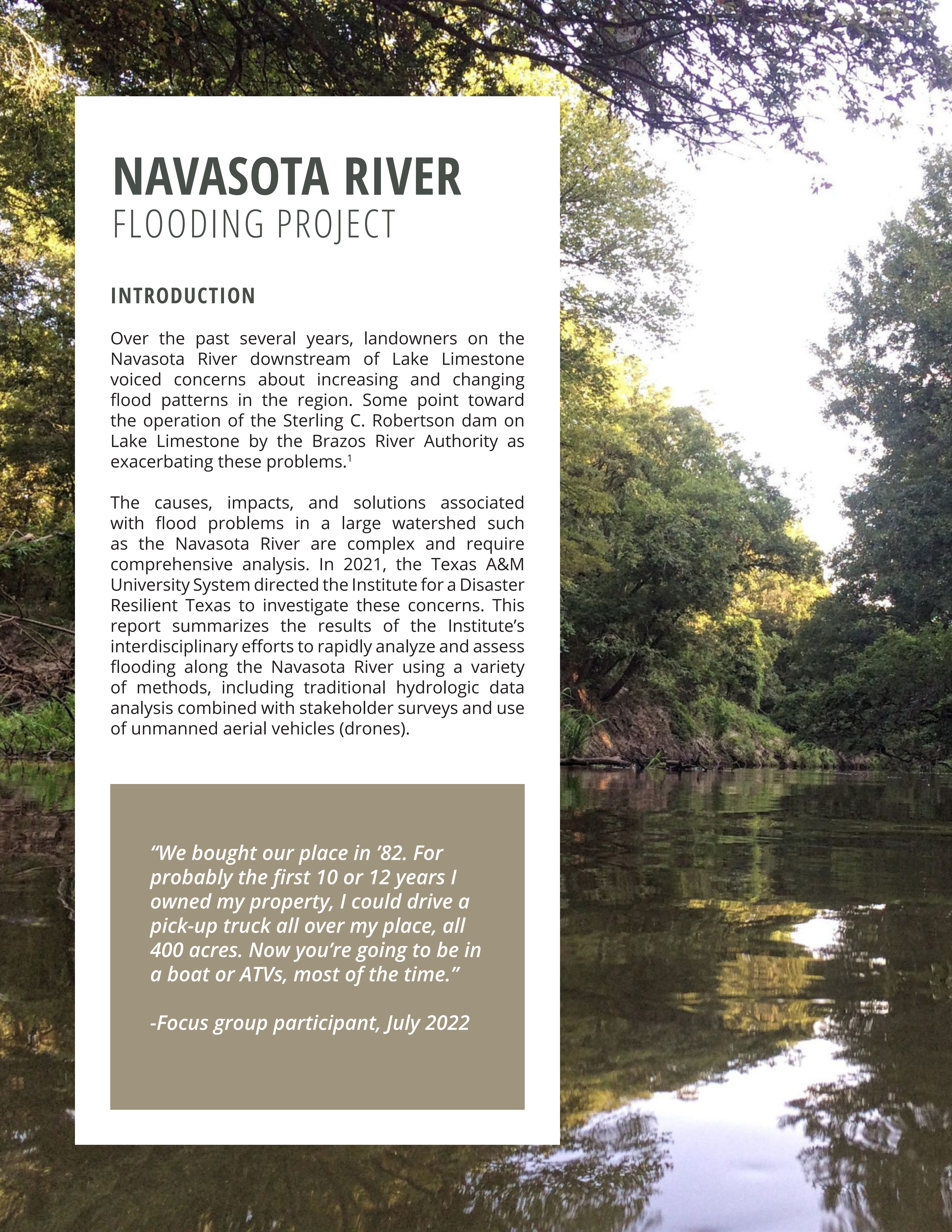
INTRODUCTION

DECEMBER 2022



NAVASOTA RIVER
FLOODING PROJECT

INTRODUCTION

Over the past several years, landowners on the Navasota River downstream of Lake Limestone voiced concerns about increasing and changing flood patterns in the region. Some point toward the operation of the Sterling C. Robertson dam on Lake Limestone by the Brazos River Authority as exacerbating these problems.[1]

The causes, impacts, and solutions associated with flood problems in a large watershed such as the Navasota River are complex and require comprehensive analysis. In 2021, the Texas A&M University System directed the Institute for a Disaster Resilient Texas to investigate these concerns. This report summarizes the results of the Institute's interdisciplinary efforts to rapidly analyze and assess flooding along the Navasota River using a variety of methods, including traditional hydrologic data analysis combined with stakeholder surveys and use of unmanned aerial vehicles (drones).

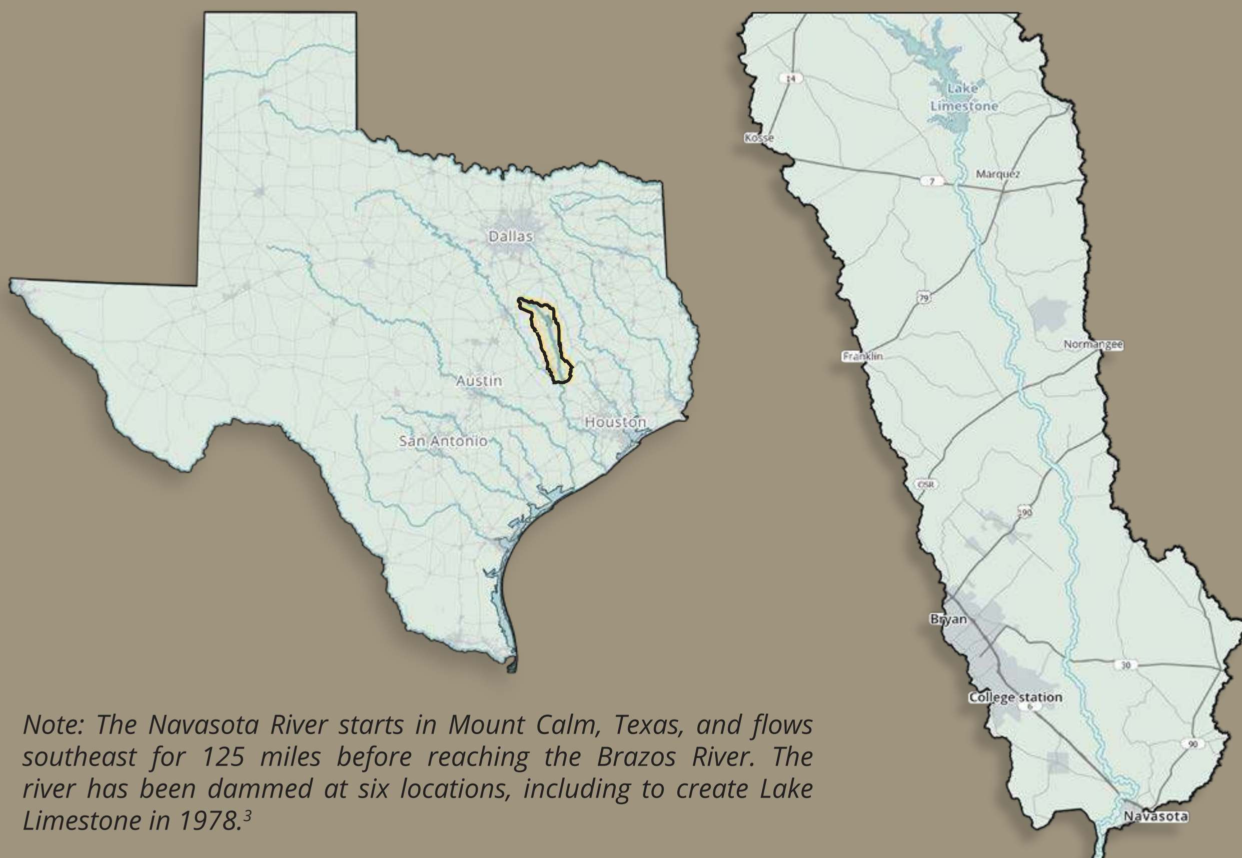
"We bought our place in '82. For probably the first 10 or 12 years I owned my property, I could drive a pick-up truck all over my place, all 400 acres. Now you're going to be in a boat or ATVs, most of the time."

-Focus group participant, July 2022

The area for this study is the Navasota River watershed, as seen in Figure 1, focused on the area south of Lake Limestone to the city of Navasota at the confluence of the Navasota River and the Brazos River.

A watershed, as defined by the Texas Watershed Steward Training Program, is "an area of land that water flows across, through, or under on its way to a stream, river, lake, or ocean."[2]

FIGURE 1: STUDY AREA



Note: The Navasota River starts in Mount Calm, Texas, and flows southeast for 125 miles before reaching the Brazos River. The river has been dammed at six locations, including to create Lake Limestone in 1978.[3]

Texas has experienced unprecedented flooding, with recent events representing some of the most significant rainfall in recorded history. In Central Texas, for example, the Memorial Day Flood in 2015 was a dramatic rainfall event. At the time, Governor Greg Abbott noted that the 500-year rainfall event was "the highest flood we've ever had recorded in the history of the state of Texas,"[4] that is, until Hurricane Harvey in August of 2017. Hurricane Harvey dropped 25 inches of rain on much of Southeast Texas over 6 days, with isolated totals of more than 60 inches. The hurricane triggered the largest disaster response effort in Texas' history.[5]

In response to the state's experiences with these historic rainfall events and based on recommendations from the Governor's Commission to Rebuild Texas (chaired by Texas A&M University Chancellor John Sharp), the state took action to improve flood resilience.[6] In 2019, the Texas Legislature created the first regional and state flood planning process organized into 15 river basin-based flood planning regions.

Coordinated by the Texas Water Development Board, each of the regions is charged with submitting their first regional flood plans in January 2023. These plans will be used to create the first state flood plan by September 1, 2024.[7] Legislation passed in 2019 also created the Institute for a Disaster Resilient Texas to, in part, "provide evidence-based information and solutions to aid in the formation of state and local partnerships to support disaster planning, mitigation, response, and recovery."[8] In line with these legislative goals, in conducting this study, the Institute communicated closely with the Lower Brazos Flood Planning Region 8 and integrated the findings and recommendations of this study with the state's planning process as much as possible.

This study piloted a multidisciplinary approach to conducting a regional flood assessment on a large scale. A critical part of the research was conducting surveys, interviews, and a focus group with area landowners to understand the nuances of the local concerns in greater detail. These interactions produced important insights, particularly in the southern part of the area (south of State Highway OSR). The 35 landowners participating in this study reported significant and changing flood impacts—including floodwaters standing on their land for a week or longer and significant property damages, economic losses, and change in land use due to flooding. A majority of the survey respondents reported experiencing one-to-two floods per year with an average of 6 feet of floodwater depth and were concerned with the length of time floodwaters remain on their properties, 10 days to 3 months in some cases (see Table 1).

Several survey participants reported that the length of time floodwater remains on their land has increased, requiring them to change agricultural production practices and other uses of their land. Many of these stakeholders remain concerned that the operation of the Lake Limestone dam could be making flooding worse but also acknowledge localized debris build up, increasing development, and other watershed-level changes as potential contributing factors.

> *"We found increased rainfall and storm intensities to be the primary driver, which has been exacerbated by increased development, debris blockages, and straightening of the river."*
>
> *-Sam Brody & Russell Blessing, December 2022*

TABLE 1: LOCAL FLOOD EXPERIENCES

FLOODS/YEAR	# OF RESIDENTS	DEPTH	DURATION	DAMAGES
<1 flood	3	0 to 0.5 feet	0 to 1-2 days	none to mild
1 flood	8	3 to 8 feet	3-5 days to 2-3 months	mild to extremely severe
2 floods	8	5 to 12 feet	3-5 days to 1 month	mild to extremely severe
3 to 5 floods	3	4 to 8 feet	3-5 days to 1 month	moderate to somewhat severe

Note: Figures reported are aggregated survey responses (n=22).

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While our study did not explicitly focus on stakeholders located above the dam, we reached out to an association of Lake Limestone property owners to gain some perspectives from people living in that area. It is important to note that stakeholders above the dam expressed divergent concerns. They believe that changes to the operation of the Lake Limestone dam (such as lowering the lake levels to mitigate downstream flooding) could impact not only their access to the lake but could reduce an important source of water supply meant to protect the region against drought.

The results of our analysis did not find that the dam was causing increased flooding downstream. Instead, we found increased rainfall, particularly high intensity rainfall, to be the primary driver, which has been exacerbated by increased development, debris blockages, and straightening of the river. Nevertheless, the experiences of the landowners who provided input for this study underscore realities of flood impacts that merit additional attention. More data collection, analyses, and localized investigations on the impacts of flooding in the watershed should continue to be pursued by local and regional jurisdictions and planning groups.

Varying experiences and contrasting views about the causes and impacts of regional flooding over such a large area are to be expected; our hope is that this study helps frame these issues using the best available data and most rigorous research methods to direct resources toward the most impactful regional mitigation strategies. Fully addressing large scale regional flooding issues moving forward will take more research and action than the scope and timeframe of our study. The Institute stands ready to continue collaboration with local stakeholders, the regional flood planning process, and other state efforts to continue improving flood resilience in Texas.

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METHODS

DECEMBER 2022

METHODS

An interdisciplinary team of researchers led by Texas A&M's Institute for a Disaster Resilient Texas conducted this study from late 2021 to September 2022, bringing together expertise from civil engineering, hazard mitigation, aerial imaging and 3D mapping, social science, and public policy. Researchers collected as much relevant data as possible, including nearly a century's worth of rainfall and streamflow data, historic imagery dating back to the 1970's, unmanned aerial vehicle (drone) footage of areas around bridge crossings and two properties along the Navasota River, and release data from the Sterling C. Robertson dam on Lake Limestone.

The research was coordinated with the Region 8 Lower Brazos Flood Planning Region (the state flood planning region to which the Navasota River belongs) and provided data and recommendations for consideration as part of the Texas Water Development Board's ongoing statewide flood planning process. Overall, this study piloted a unique, multidisciplinary methodology to rapidly investigate flood issues and provide decision support—a process the Institute for a Disaster Resilient Texas plans to replicate on future projects.

Additional details regarding methodology, data sources, and technical findings are included in the Supplementary Materials to this report, available at:

https://idrt.tamug.edu/navasota-river-flooding-project/

RESEARCH QUESTIONS & METHODS

WHAT ARE LOCAL EXPERIENCES WITH FLOODING?

Lead researcher: Dr. Ashley Ross, Texas A&M University at Galveston

Surveyed and interviewed landowners and tenants to assess flooding impacts and identify trends.

WHAT DOES THE RIVER LOOK LIKE?

Lead researcher: Dr. Robin Murphy, Texas A&M University

Collected drone imagery to understand how obstructions and riverine characteristics could influence flood risk.

HOW HAS THE RIVER CHANGED?

Lead researchers: Dr. Rocky Talchabhadel & Ed Rhodes, M.S., Texas Water Resources Institute

Mapped the river using historic imagery to see how the river path has changed over time.

HOW HAVE THE NATURAL AND BUILT ENVIRONMENT CONDITIONS CHANGED?

Lead researcher: Dr. Ali Fares, Prairie View A&M University

Analyzed rain, streamflow, and land use data to see how drivers of flood risk have changed over time.

HOW HAS FLOOD RISK CHANGED?

Lead researcher: Dr. Andrew Juan, Rice University

Developed models and scenarios to understand how operation of the Lake Limestone dam and other factors, such as terrain and rainfall, could influence downstream flooding.

FINDINGS

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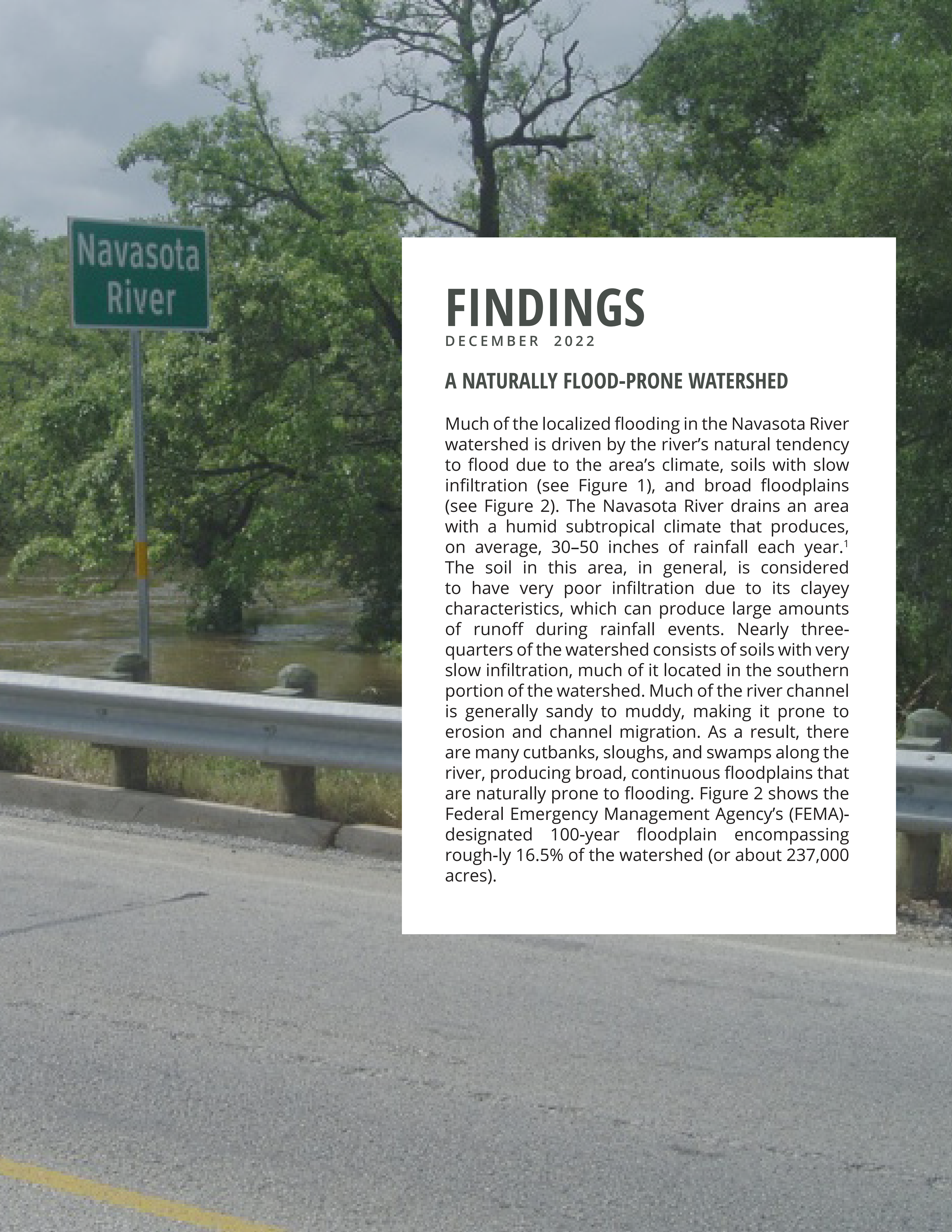

FINDINGS

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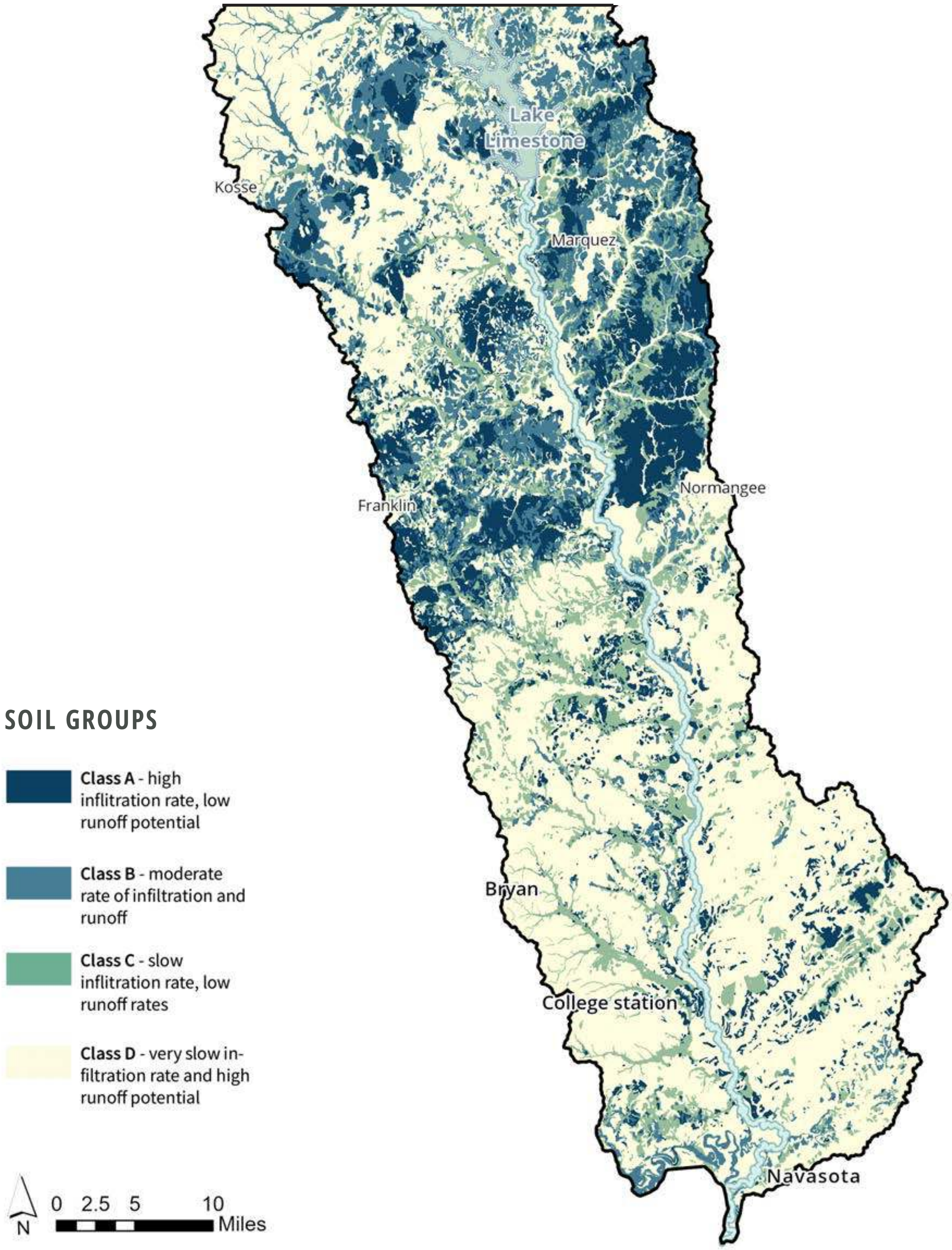
A NATURALLY FLOOD-PRONE WATERSHED

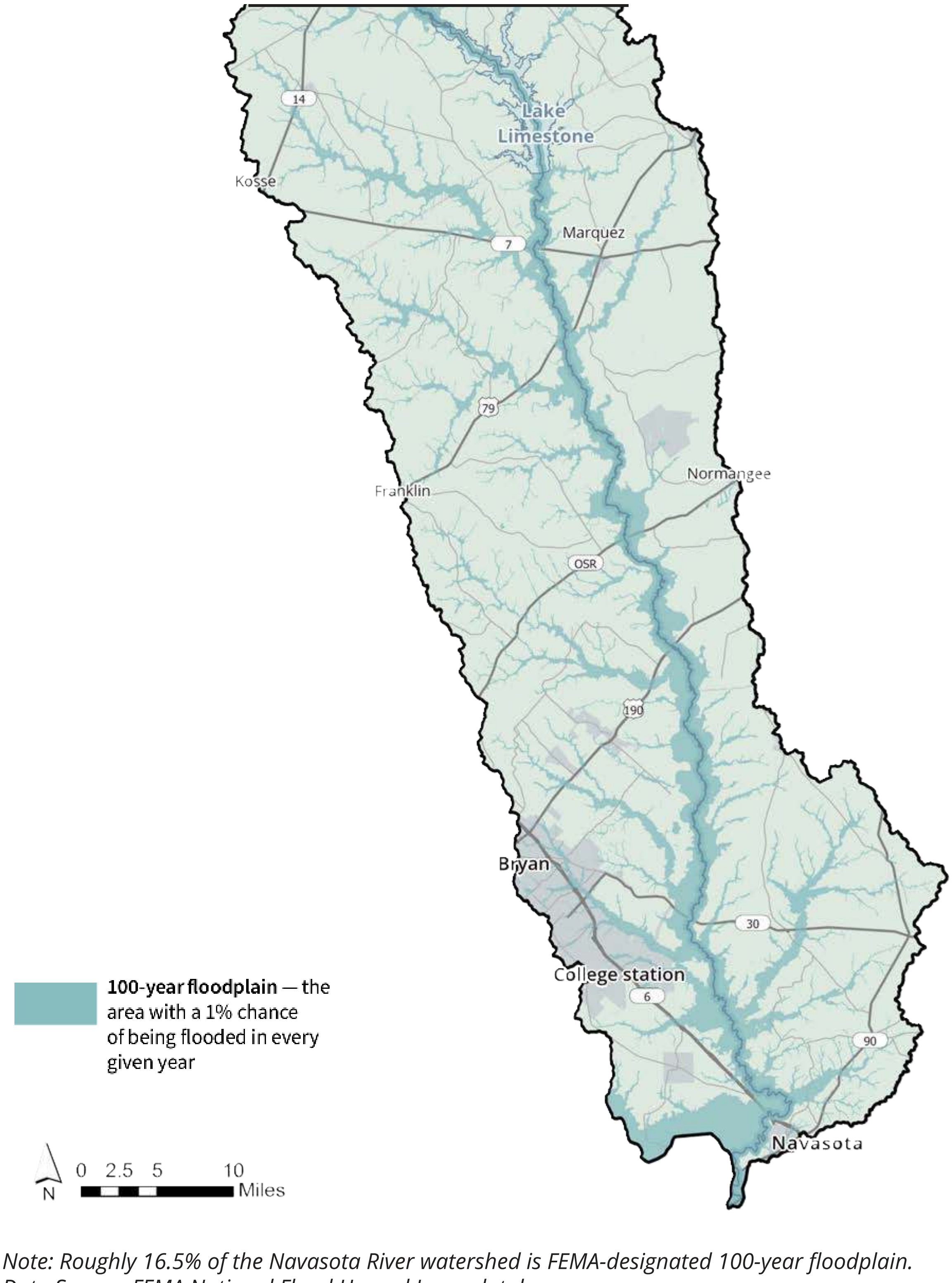
Much of the localized flooding in the Navasota River watershed is driven by the river's natural tendency to flood due to the area's climate, soils with slow infiltration (see Figure 1), and broad floodplains (see Figure 2). The Navasota River drains an area with a humid subtropical climate that produces, on average, 30–50 inches of rainfall each year.[1] The soil in this area, in general, is considered to have very poor infiltration due to its clayey characteristics, which can produce large amounts of runoff during rainfall events. Nearly three-quarters of the watershed consists of soils with very slow infiltration, much of it located in the southern portion of the watershed. Much of the river channel is generally sandy to muddy, making it prone to erosion and channel migration. As a result, there are many cutbanks, sloughs, and swamps along the river, producing broad, continuous floodplains that are naturally prone to flooding. Figure 2 shows the Federal Emergency Management Agency's (FEMA)-designated 100-year floodplain encompassing rough-ly 16.5% of the watershed (or about 237,000 acres).

FIGURE 1: SOIL INFILTRATION MAP



Note: Nearly three-quarters of the Navasota River watershed consists of soils with very slow infiltration which can produce large amounts of runoff during rainfall events. Data Source: Soil Survey Geographic Database (SSURGO).[2]

FIGURE 2: FEMA 100-YEAR FLOODPLAIN



Note: Roughly 16.5% of the Navasota River watershed is FEMA-designated 100-year floodplain.
Data Source: FEMA National Flood Hazard Layer database.

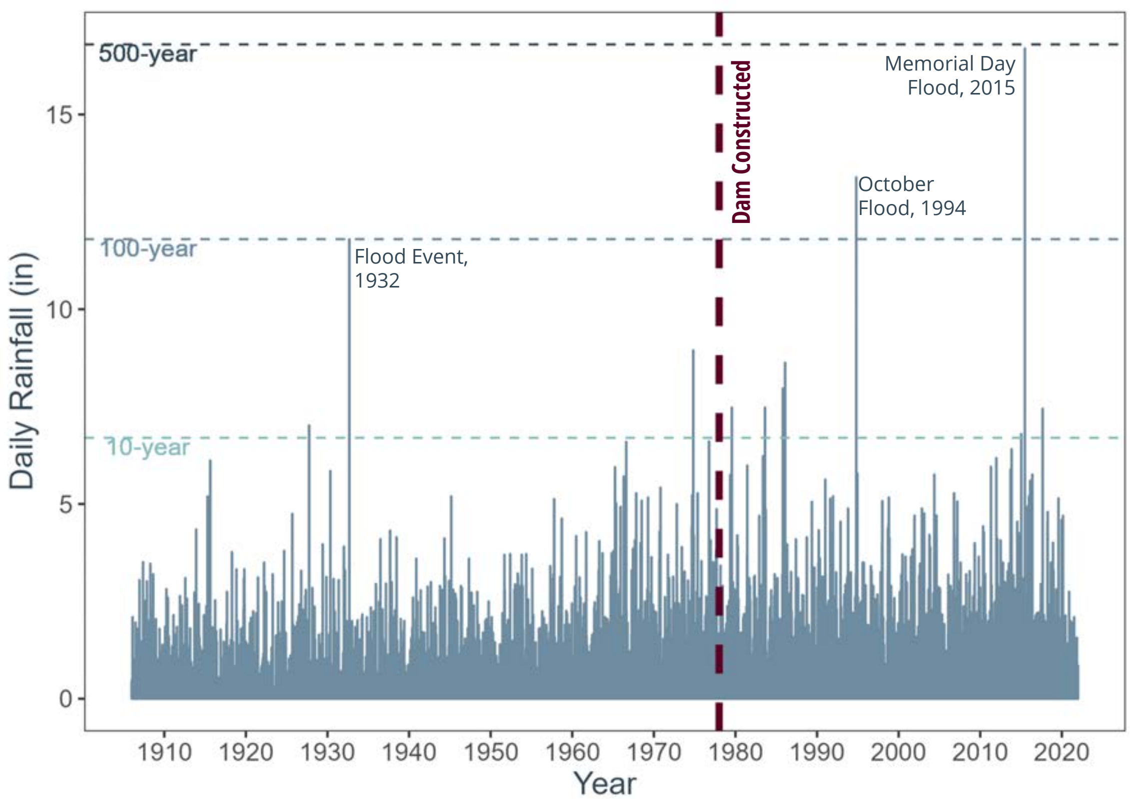
THE UNDERLYING DRIVERS OF INCREASING FLOOD RISK

Several trends contribute to the increase in flooding and associated adverse impacts within the watershed. Multiple underlying processes, including increasing rain amounts over time, expansion of impervious surfaces as a result of development, a buildup of debris at or near bridge crossings, and a straightening river path, have contributed to flooding observed by residents living along the Navasota River's banks.

Increasing Rainfall

The primary driver of flooding is rainfall, particularly high intensity rainfall events that can overwhelm the natural drainage capacity of the soil. Since the Sterling C. Robertson dam at Lake Limestone was constructed, there have been 10 significant rainfall events: one 100-year event (October 1994), one 500-year event (Memorial Day Flood of 2015), and eight 10-year events throughout the watershed. Before the dam's construction, there was only one recorded 100-year event in 1932 and three 10-year rainfall events throughout the watershed (see Figure 3).[3] Many of the recent large rainfall events have occurred after multiple days of rainfall that had already saturated the soil. This resulted in increased runoff, ponding, and downstream flooding.

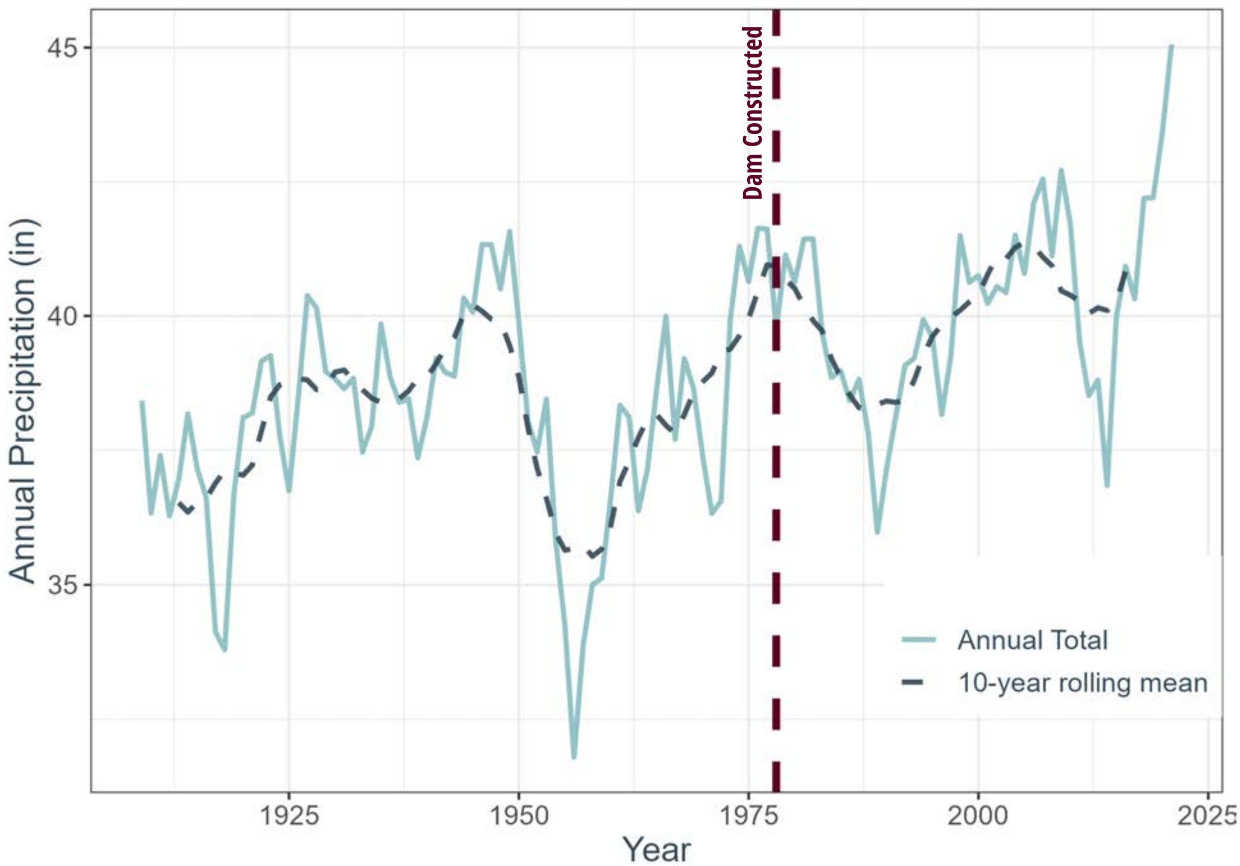
FIGURE 3: DAILY MAXIMUM RAINFALL



Note: Daily maximum rainfall across the entire watershed indicates there has been one 100-year event, one 500-year event, and eight 10-year events since the construction of the Lake Limestone dam. Data Source: Daily rainfall data from four gauge locations: Navarro Mills Dam, Mexia, Franklin, and College Station Easterwood Field.[4]

Within the watershed, rainfall trends have increased over time, punctuated by periods of drought. As shown in Figure 4, the most dramatic upward trend in rainfall began in 1980. From 2009 to 2018 there were five minor floods of about 6 inches, four moderate floods of about 8 inches each, and the Memorial Day flood in 2015 that generated more than 16 inches of rain in some locations. Notably, 2015 was one of the wettest years on record.

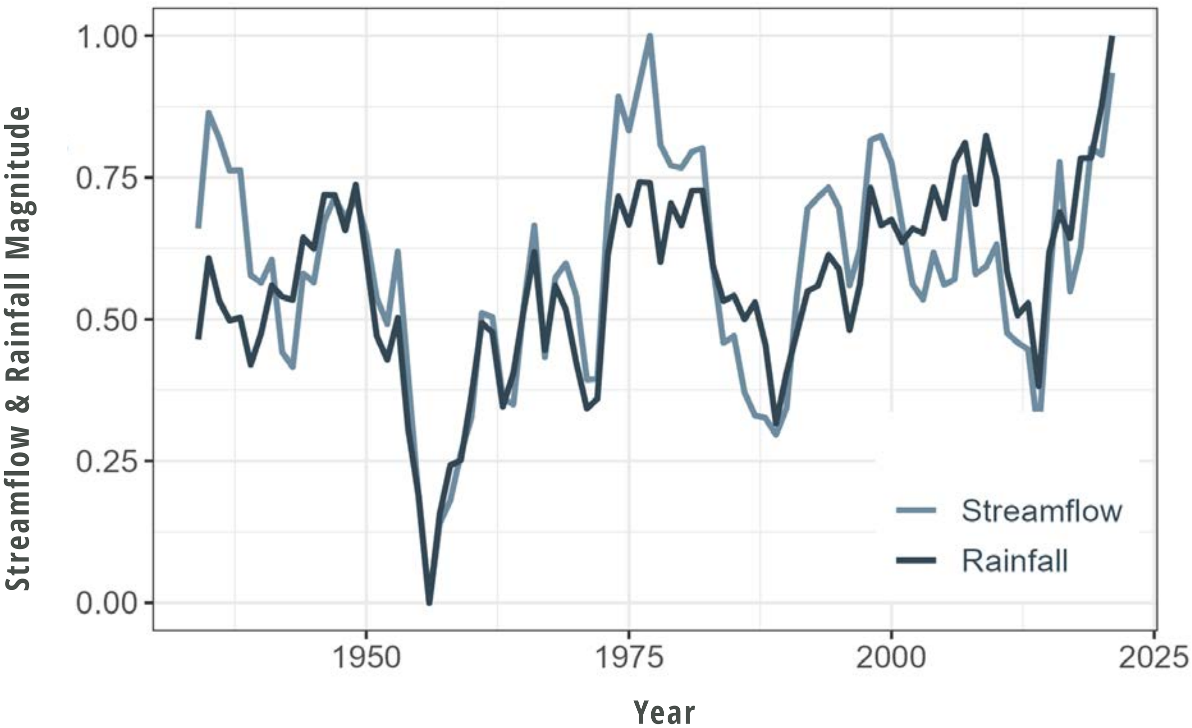
FIGURE 4: ANNUAL RAINFALL TRENDS



Note: Rainfall trends have been increasing over time despite periods of drought. Graph shows average annual rainfall amounts for the Navasota River watershed. Data Source: PRISM Climate Data.[5]

With more rainfall comes increasing streamflow and the subsequent increasing risk of flooding of adjacent land due to river overbanking. Figure 5 illustrates the correlation between rainfall and streamflow. Moreover, as streamflow increases, so too does the amount of water flowing into the reservoir, resulting in more dam releases to maintain the reservoir level. An analysis of Lake Limestone dam releases found that one-third of the large releases (i.e., exceeding 10,000 cubic feet per second) over 37 years occurred in the last 7 years.

FIGURE 5: RELATIONSHIP BETWEEN RAINFALL AND STREAMFLOW



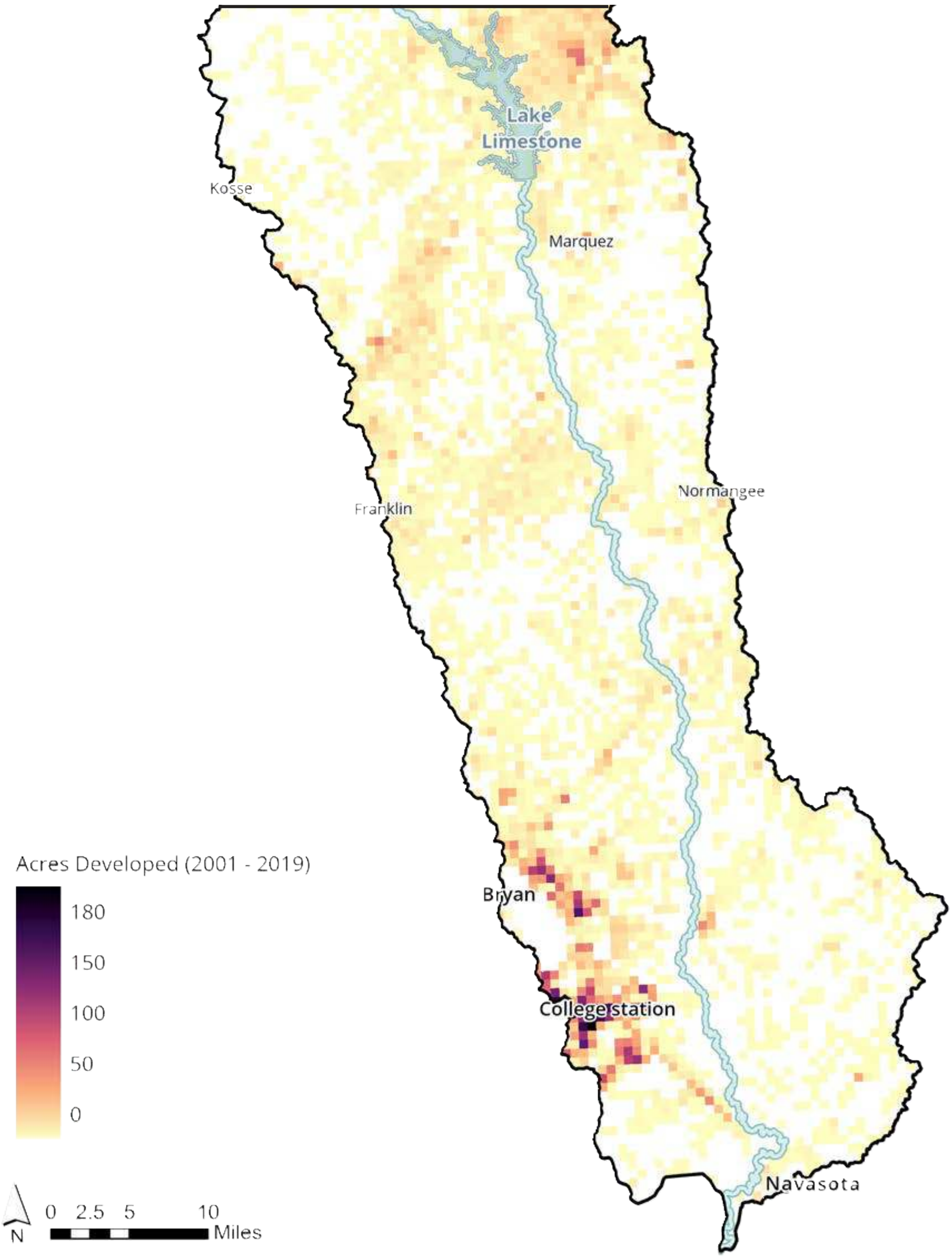
Note: There is a strong relationship between rainfall and streamflow trends. Increased rainfall has resulted in increased streamflow requiring a corresponding increase in dam releases. Graph shows normalized rainfall and streamflow amounts for comparison. Data Sources: PRISM Climate Data & USGS Streamflow Gauge Data (08110500).[6]

INCREASING DEVELOPMENT & IMPERVIOUS SURFACES

While development in flood-prone areas, such as the 100-year floodplain, puts structures at risk, the way in which development occurs outside and upstream of flood-prone areas also contributes to flood risk. Urbanization, including the expansion of impervious surfaces such as roads, rooftops, and parking lots, is a major contributor to flood impacts.[7]

Since 2001, the Navasota River watershed has added about 19,000 acres of new development, much of it in the Bryan-College Station area, creating the largest expanse of impervious surface in the region (see Figure 6). In all, this development replaced approximately 13,300 acres of pasture, 4,500 acres of forest, and 150 acres of wetlands. Urban and suburban development can lead to reduced infiltration, increased runoff, and higher peak discharges in nearby streams, exacerbating flood risk downstream. In fact, our analysis found that annual streamflow downstream of the Bryan-College Station area increased by about 12% as a result of the increase in development since 2001, with significant variation across wet and dry months. Although measures such as requirements for retention ponds may mitigate this impact, previous studies have shown that flood risk can increase despite such efforts.[8]

FIGURE 6: DEVELOPMENT FROM 2001 TO 2019



Note: Since 2001, the Navasota watershed has added 19,000 acres of new development, much of it in the Bryan-College Station area. Data Source: USGS National Land Cover Database.[9]

RIVERINE DEBRIS

Woody debris and sediment can be transported by rivers and accumulate at bridge piers, particularly during large rainfall events. Even though the erosion of banks and transport of woody debris by streams draining forested watersheds is a natural process, flood hazard is often considerably increased whenever large amounts of instream debris prevent or impede the flow of water.[10] This impact came as no surprise to the local landowners in the Navasota River watershed study area. In fact, one resident participating in this study said: “everywhere we have a bridge crossing, we have another dam.”

Over the course of this study, researchers flew unmanned aerial vehicles (drones) from five bridge crossings along the Navasota River to investigate conditions and identify whether there were any blockages. One bridge (at Long Trussel Road, or County Road 162) had a major blockage identifiable from aerial footage (see Figure 7). The other four bridges flown had either minor constrictions, were free of debris, or were obscured by heavy tree canopy. Areas of woody debris upstream of State Highway 30 and State Highway 6 and downstream of State Highway OSR could contribute to future blockages at bridge intersections. The dense tree canopy around State Highway 190 made it difficult to visually inspect the river and identify any potential debris and/or obstructions. Further investigations of these areas could point to the causes of some of the localized flooding issues reported during this study.

FIGURE 7: RIVERINE DEBRIS AT COUNTY ROAD 162

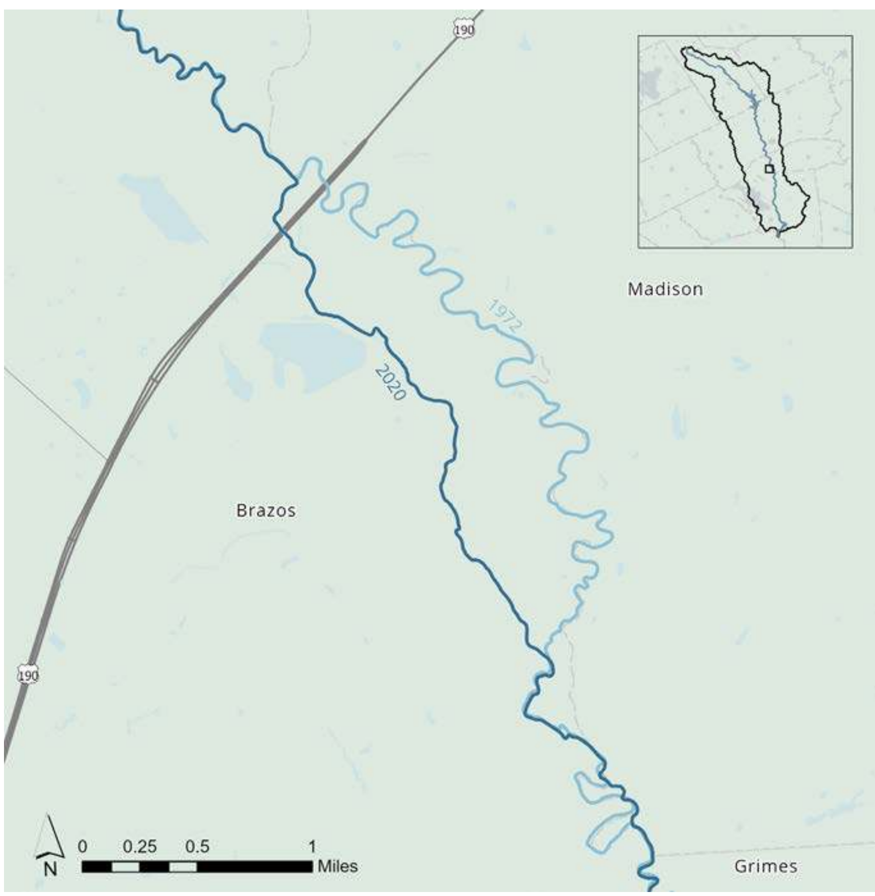
Note: Significant debris obstruction where Long Trussel Road (County Road 162) crosses the Navasota River.

A STRAIGHTENING RIVER PATH

The shape of a river can impact flooding. Typically, meandering rivers are characterized by slower moving water, which results in less erosion and downstream flooding. In contrast, rivers that are straighter often result in higher velocity streamflows that can cause erosion of the streambank and produce greater downstream flood risk. Rivers naturally change over time in response to the climate and natural conditions, such as the soil and topography, of the watershed they are within.[11]

The Navasota River has been an actively migrating river for centuries, frequently producing local channel shifts, abandonment of meander bends in some areas, and the creation of new or exaggerated bends in other areas.[12] By examining aerial photographs dating back to the 1970s, this study found that the Navasota River (from State Highway OSR to the Brazos River confluence) has significantly straightened over time, resulting in a river that is roughly 2.7 miles shorter than it was in 1972. Most of this change is between Democrat Road and Highway 190 (see Figure 8), where there has been a westward shift and loss of natural bends, creating a straighter, shorter river section. This straightening and shortening of the river has likely resulted in faster moving water, increased erosion and debris transport, and increased downstream flood risk.

FIGURE 8: NAVASOTA RIVER FROM STATE HIGHWAY OSR TO BRAZOS RIVER CONFLUENCE



Note: The Navasota River has significantly straightened over time, resulting in a river that is roughly 2.7 miles shorter than it was in 1972 and likely resulting in increased downstream flood risk. Data Source: USDA Aerial Photography Field Office and National Agricultural Imagery Program.[13]

THE IMPACT OF THE DAM ON DOWNSTREAM FLOODING

Dam Operations and Their Potential Influence on Flooding

A dam's influence on downstream flooding is primarily associated with the function that its associated reservoir serves. Reservoirs are typically classified as water supply, flood control, or dual-purpose, each of which have their own distinct operating procedures. The Sterling C. Robertson dam on Lake Limestone was constructed on the Navasota River to create Lake Limestone in 1978 (see Figure 9). Lake Limestone, owned and operated by the Brazos River Authority (BRA),[14] is among the 150 large water supply reservoirs in Texas built to meet both public and private demand. Water supply reservoirs are the most common type of reservoirs in Texas—the state has 35 dual-purpose reservoirs (with enough storage for both water supply and flood control) and eight flood control reservoirs.[15]

Dam releases for water supply reservoirs are guided by two principles: 1) the reservoir is kept as full as possible to meet downstream water supply demands, and 2) the rate and amount of water released is not to exceed the rate and amount of water received. The second principle is often referred to as the "run-of-the-river operations," in which only additional water that flows into the reservoir is released during rainfall events. In other words, the volume of water in the reservoir before and after a rainfall event should be equivalent.[16] Therefore, if the dam is releasing no more floodwater than would have flowed down the river in its absence, the releases should not result in any additional flooding of downstream properties than would have occurred in the dam's absence.

Water supply reservoirs are not generally designed for flood control, however, they can provide some flood mitigation benefit by reducing peak flows during significant rainfall events.[17] For example, Lake Limestone has some additional capacity (approximately 33,000 acre-feet) above its normal pool elevation designed for temporary storage during rainfall events. This temporary storage allows the reservoir to store some stormwater, which can sometimes result in decreased downstream flood depths. This additional capacity acts as a buffer that slows the movement of water, resulting in a delay in the timing of flooding, giving BRA the ability to send out alerts to downstream property owners in advance.

However, some landowners downstream of Lake Limestone are concerned that releases from the reservoir have been contributing to increases in flooding and changing flood patterns since the construction of the Lake Limestone dam. The BRA is aware of these concerns and report that they operate the dam as it was designed to have minimal impact on downstream flooding.

Similar concerns about the Lake Limestone dam's impact on downstream flooding were investigated in 1986. Only eight years after the dam had been constructed, a landowner reported that dam releases were directly contributing to and worsening floods on their property. An investigation concluded that releases never exceeded inflows and had decreased the flood peaks during the storms of concern.[18] The 1986 study concluded that the increase in floodwater depth on the property in question was the result of a diked road downstream of the property that had been causing water to back up and flood the land. In some ways, the Institute's study can be viewed as an extension of the 1986 analysis with more data, more advanced models, and a broader multidisciplinary look at other potential flooding factors.

OPERATING WATER SUPPLY RESERVOIRS FOLLOW KEY PRINCIPLES:

- *Kept as full as possible to meet downstream water supply demands.*
- *Release as much flood water as received and no more.*[19]

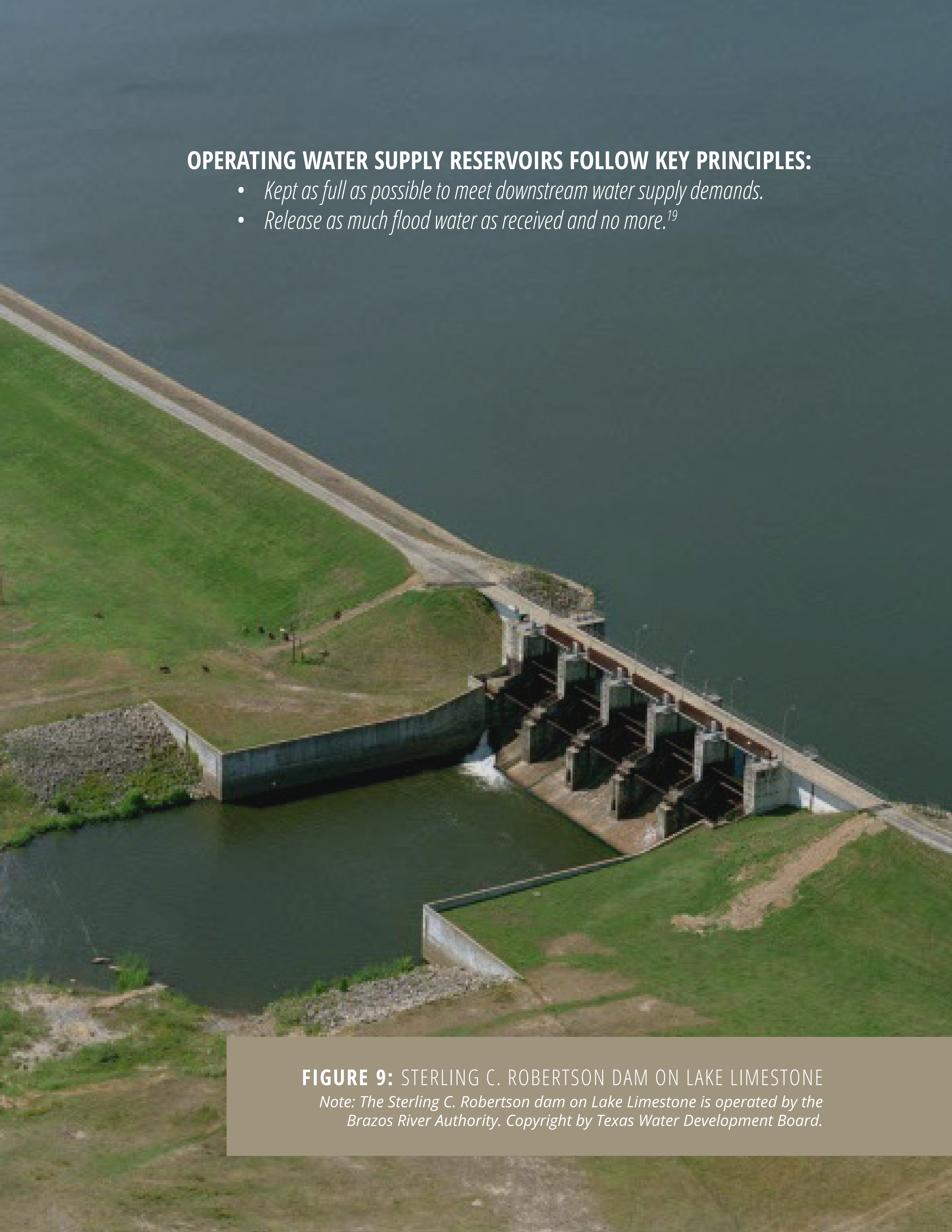


FIGURE 9: STERLING C. ROBERTSON DAM ON LAKE LIMESTONE

Note: The Sterling C. Robertson dam on Lake Limestone is operated by the Brazos River Authority. Copyright by Texas Water Development Board.

The Impact of Lake Limestone Dam Releases on Downstream Flooding

This study evaluated the potential impact of the Lake Limestone dam on downstream flooding as it is currently designed to be operated as a water supply reservoir. (This study did not explore the impact of potential changes to the purpose, design, or operations of the dam such as using the dam explicitly for flood control by making pre-releases before a predicted rain event.) Researchers analyzed and compared two past rainfall events with a modeled “no dam” scenario to evaluate flood timing (how soon floodwaters arrive), flow (the speed and volume of the floodwater moving in the river), depth (how deep the floodwaters get), and duration (how long it takes floodwater to recede). The analysis found that, when compared to a “no dam” scenario, the Lake Limestone dam delays when flooding occurs and does not have any consistent or significant impact on flow, depth, or duration of flooding.

Researchers conducted a flood impact analysis using a two-dimensional (2D) hydraulic model (HEC-RAS 2D)[20] to simulate two recent storms (April 11-16, 2017, and June 1-6, 2021) that resulted in dam releases. These storms were selected primarily because they triggered large dam releases according to historic dam release data. The distribution of the rainfall for both storms was similar in areas upstream of the Lake Limestone dam (approximately 4 inches of total rainfall for each event). Downstream of the dam, the geographic distribution of the two storms’ rainfall was noticeably different, with most areas accumulating less than 2 inches of rainfall during the April 2017 storm, and some areas getting more than 3 inches during the 2021 storm.

After validation, these two rainfall events served as baseline scenarios to compare what flooding would have looked like if there had been no dam. This “no dam” scenario assumes that there was no flood control structure present to detain the inflow upstream of the dam. This study uses four watchpoints (see Figure 10) along the Navasota River to compare the impacts of flooding between the two scenarios—“with dam” and “no dam.” Watchpoints 1 and 2 coincide with the locations of the two physical U.S. Geological Survey (USGS) gauges (gauge numbers 08110500 and 08110800)[21], while Watchpoints 3 and 4 were virtual watchpoints selected to evaluate the impacts of the Lake Limestone dam releases at locations farther downstream.

This study modeled and compared the maximum depth (i.e., water surface elevation) and peak flow (i.e., cubic feet per second) of the water, along with the timing of the flood at each watchpoint for both scenarios. This study also measured the duration of flooding above the gauges’ flood stage levels for Watchpoints 1 and 2. The modeling and comparison results are detailed in the following sections.

NAVASOTA RIVER
FLOODING PROJECT

This study concluded that the dam has not exacerbated flooding downstream in any noticeable way. The dam's most notable effect was on the timing of when the flooding occurred. The analysis found that the Lake Limestone dam delays when flooding occurs and generally, the closer someone is to the dam, the greater the lag time will be. The analysis did not find significant differences between extent, depth, and duration of flooding of the two modeled rainfall events compared to the "no-dam" scenario.

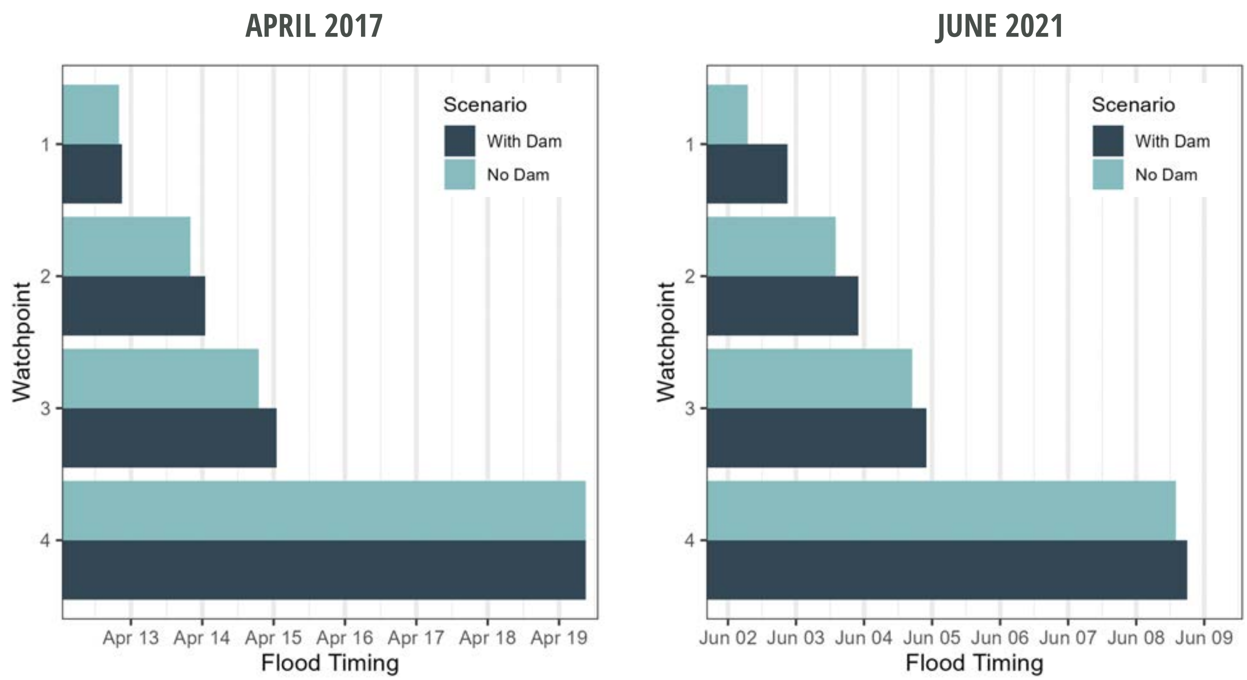
FIGURE 10: NAVASOTA RIVER FLOOD IMPACT WATCHPOINTS

Note: Navasota River flood impact watchpoints for scenario analysis. There are only two physical USGS gauges in the Navasota River watershed at Watchpoints 1 and 2.

Timing of the Flooding

This study found that the Lake Limestone dam's most notable effect was on delaying the timing of when the flooding occurred. Compared to a "no dam" scenario, the dam delayed flooding for both rainfall events by 1 to 14 hours, with the longest delays being closest to the dam (see Figure 11). The closer a property is to the dam, the greater the percentage of water comes directly from dam releases versus local rainfall, so the dam holding water has a greater effect. The farther a property from the dam, the more local rainfall below the dam also contributes to flooding on that property, diluting the dam's impact. Thus, the analysis revealed that by Watchpoint 4 the influence of rainfall becomes the dominating factor resulting in a negligible difference in timing of flooding between the "with dam" and "no dam" scenarios.

FIGURE 11: FLOOD TIMING WITH AND WITHOUT THE DAM



Note: The timing of the peak water surface elevation for the April 2017 and June 2021 events modeled with and without the dam. For both events, the dam delays when floodwaters arrive, with the delay being greater closer to the dam.

The Duration of Flooding

The second aspect of flooding this study investigated downstream of the Lake Limestone dam was the duration of flooding. The study analyzed how long water stayed above the flood stage (as measured by the two USGS gauges in the watershed at Watchpoints 1 and 2). The findings on flood duration did not show a clear trend (see Table 1). In some cases, the dam increased duration (Watchpoint 1 during April 2017 event) and in others it decreased duration (Watchpoints 1 and 2 during the June 2021 event).

How much rainfall occurred in which locations has at least as much impact on flood duration, and in some cases more, than the dam releases. In some cases, the peak rainfall intensity may align with the peak of dam releases causing flooding to be more extreme, but over a shorter period of time. In other instances, the timing may result in slightly less flooding but lasting a longer time.

TABLE 1: FLOOD DURATION WITH AND WITHOUT THE DAM

April 2017 Duration

WATCH POINT	WITH DAM	WITHOUT DAM	DAM IMPACT
1	137 hours	119 hours	18 hours longer
2	63 hours	64 hours	1 hour longer

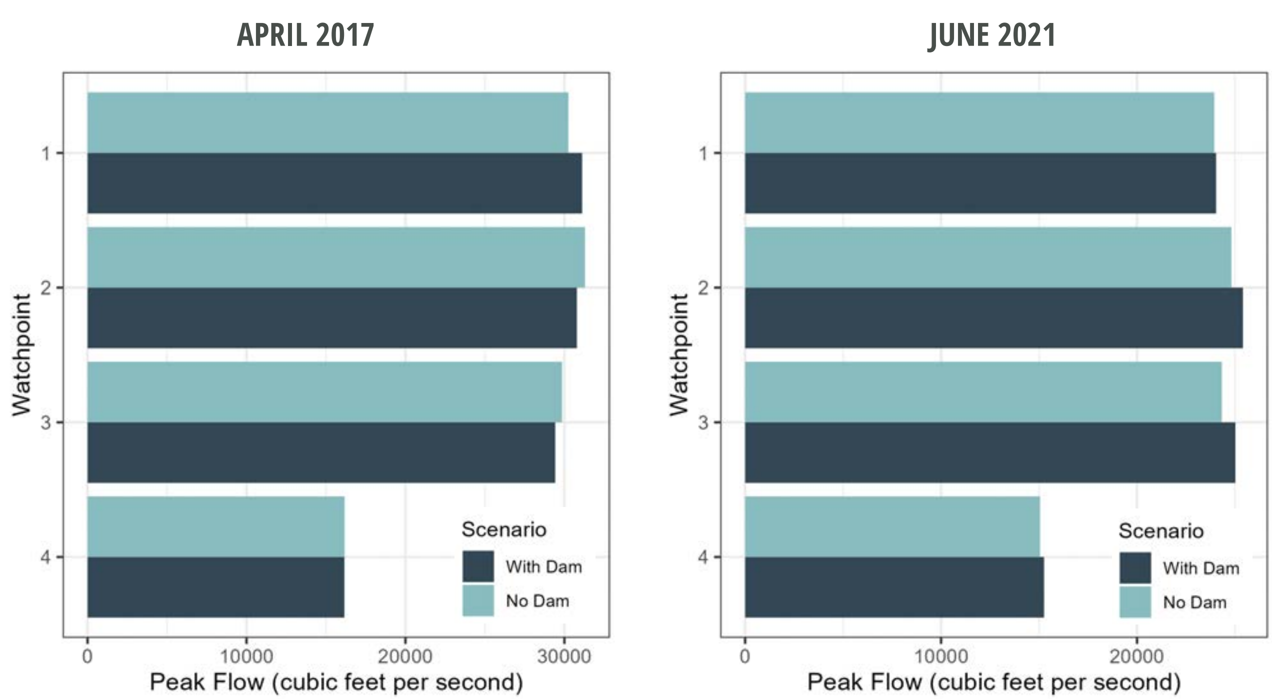
June 2021 Duration

WATCH POINT	WITH DAM	WITHOUT DAM	DAM IMPACT
1	190 hours	199 hours	9 hours shorter
2	62 hours	64 hours	2 hours shorter

The Flow & Depth of Water

Flow and depth had similar characteristics between the "with dam" and "no dam" scenarios. The Lake Limestone dam had both positive and negative impacts on flow and depth in both scenarios for both events (see Figure 12). For flow, the difference between the two scenarios was only 1% or 2% (both positive and negative). For depth, the two scenarios differed by only an inch (both positive and negative).

FIGURE 12: PEAK FLOW WITH AND WITHOUT THE DAM



Note: Navasota River peak flow rates during the April 2017 and June 2021 events modeled with and without the dam show minimal differences across all watchpoints.

RIVER MANAGEMENT AND FLOOD RISK CONCERNS

Some downstream stakeholders have ongoing concerns about the role of the Brazos River Authority in regional flooding and mitigation activities.

This study included a survey, focus group, and interviews with landowners along the Navasota River. The sample was relatively small and self-selected (22 survey respondents, 5 interviews, and 8 focus group participants) but produced useful information about the local knowledge and lived experiences of individuals who own or lease land along the Navasota River.

As described in the Introduction section of this report, some stakeholders attribute the increase in flooding and flooding duration to releases from the Lake Limestone dam. The Brazos River Authority's (BRA)'s management of the dam dominated these stakeholders' concerns regarding the effect of flooding on their properties. However, landowners acknowledged increased development and debris in the river as factors contributing to flooding.

Overall, study participants indicated that the roles and responsibilities of various government agencies involved in managing the Navasota River - and flooding, in general - are not clear to landowners. Many stakeholders wanted to know who is responsible for dredging and clean-up of the river, including clearing debris around bridges. As one focus group participant noted, "No one claims responsibility for coming in, cleaning out the river."

Overall, when asked about flood management, survey participants held the state government most responsible but did not have a clear view of the roles of specific state agencies regarding flooding.

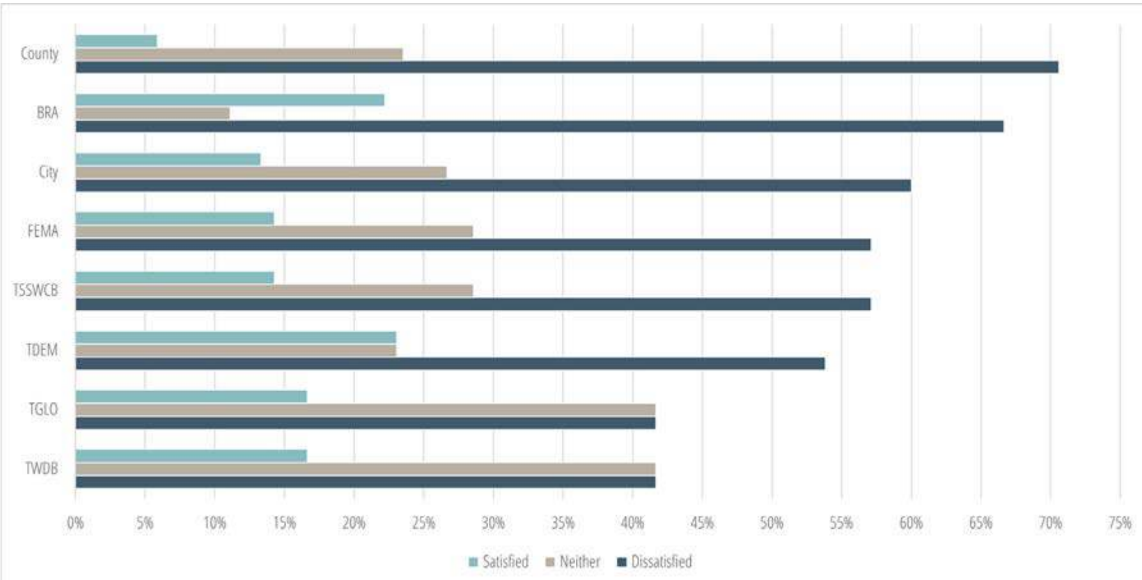
Survey participants were asked to evaluate how satisfied they are with the following groups for protection of their property from flooding: city government, county government, the BRA, the Texas State Soil and Water Conservation Board (TSSWCB), the Texas Division of Emergency Management (TDEM), the Texas Water Development Board (TWDB), the Texas General Land Office (TGLO), and FEMA.

"No one claims responsibility for coming in, cleaning out the river."

-Focus group participant, July 2022

As shown in Figure 13, more survey participants were dissatisfied than satisfied. County government was the most poorly rated, with 71% of participants saying they were dissatisfied with this group. The BRA followed closely behind with 67% of participants reporting dissatisfaction. TDEM and BRA received the most satisfaction percentages with 23% and 22% of survey participants, respectively.

FIGURE 13: RESULTS OF STAKEHOLDER SATISFACTION OF GOVERNMENT GROUPS



Note: More survey participants were dissatisfied than satisfied with government agencies' protection of their property from flooding. Response options included "extremely dissatisfied," "dissatisfied," "neither satisfied nor dissatisfied," "satisfied," or "extremely satisfied." These categories were collapsed for reporting purposes. Figures reported represent aggregated survey responses (sample size=22).

This study revealed polarization in stakeholders' views of the BRA. While 67% of survey respondents reported they were dissatisfied with the BRA's protection of their property from flooding, focus group participants noted satisfaction with the BRA's dam release notifications. They reported using these notifications to prepare for flooding by moving tractors, equipment, and livestock out of the river bottom. Most focus group participants said they are able to judge, through experience, the approximate time to expect flooding on their property (given the timing of the release from Lake Limestone) and the depth of flooding to expect (given the volume of the release). As one participant explained: "They tell you how many cubic feet per second, how many gates, and how many cubic feet they've opened and they're letting out. So just based on history, I know what that's going to do to my property." Overall, these notifications were perceived as flood warnings with sufficient information to prepare accordingly.

LIMITATIONS

This study analyzed available watershed-level data and made conclusions about the primary drivers of flooding in the region with reasonable confidence. However, data limitations required some generalizations and did not allow for more nuanced analysis of the very localized, parcel-level concerns expressed by some stakeholders. In particular, the limited/self-selected survey participants expressed the greatest concern with flooding in the lower portion of the watershed (see Figure 14), while this study's models of predicted impacts of the dam indicated more significant impacts closer to the dam.

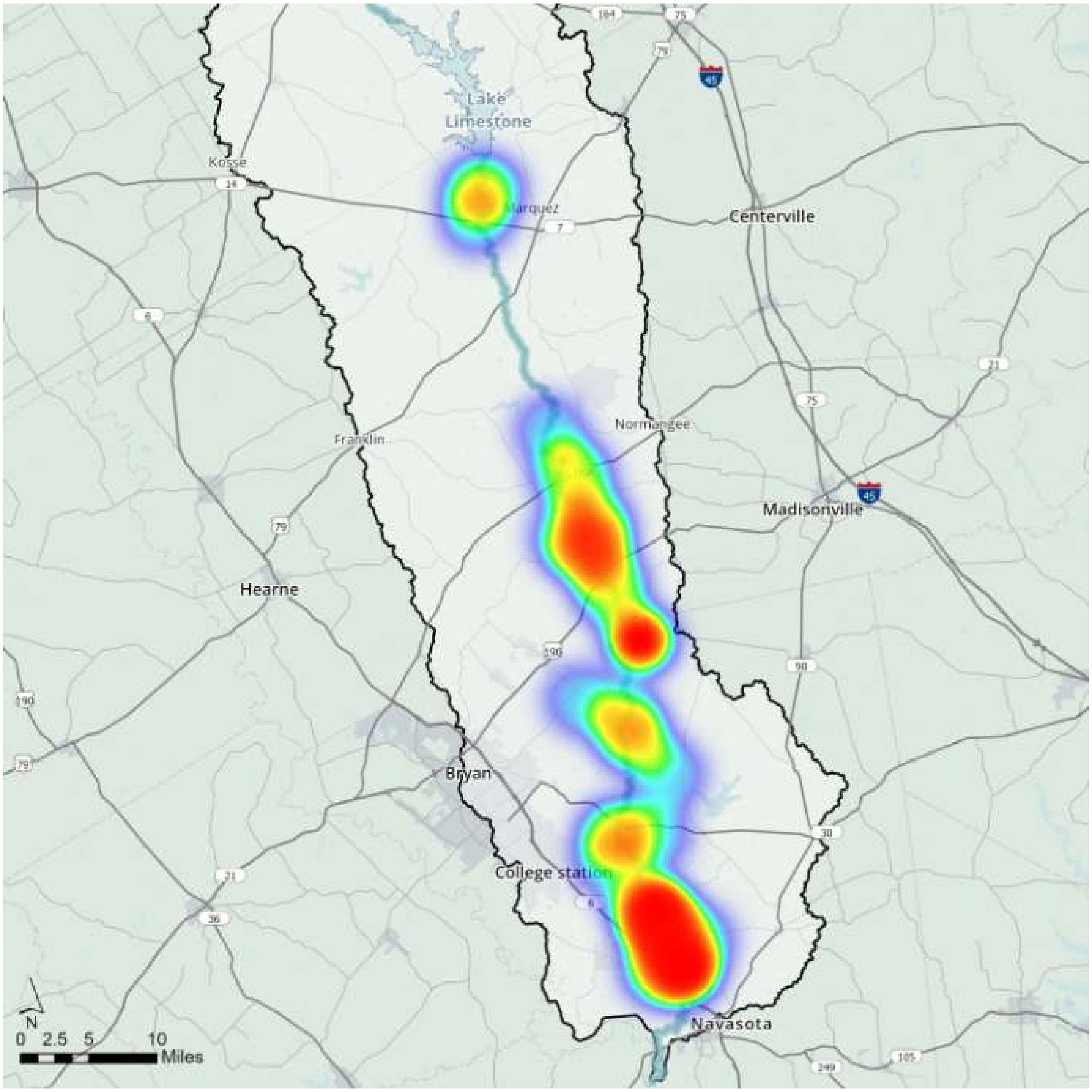
Addressing data gaps identified by this study's researchers would improve future studies and help identify and optimize future flood reduction strategies in the watershed.

Although this study's flood risk model produced a reliable flood risk assessment and determined the role of the Lake Limestone releases on downstream flooding, there are still several ways better data could produce more reliable results. The model was limited in terms of rainfall gauge, stream gauge, soil, land cover, and topography data. The strategic placement of more rain and stream gauges would help improve the accuracy of both rainfall and streamflow estimates. Better information regarding the characteristics of the soil within the study area would provide better estimates of soil moisture conditions before a rainfall event resulting in improved runoff estimates.

More information on each land cover type's roughness characteristics, which influences how water moves through a landscape, would help fine tune the model. Data about the topography of the river bottom (e.g., riverine bathymetric data) would help better determine how much water the Navasota River can hold and improve the model's flood inundation estimates.

Finally, the potential to fully capture the benefits of drone imagery for the purpose of this study was hampered by multiple factors. Study researchers were only able to capture drone imagery over relatively short stretches because of limited access to riverfront parcels due to the complexity of identifying and coordinating with landowners. Lack of any significant rainfall events during the study period prevented the real-time assessment of flooding and localized flood concerns. Heavy, dense vegetation and tree canopies precluded study researchers' ability to get a complete picture of the river.

FIGURE 14: STAKEHOLDER IDENTIFIED FLOODING 'HOT SPOTS'



Note: This map depicts up to 5 flooding "hot spots" each survey participant identified (sample size=22). Stakeholders are primarily concerned about flooding in the lower portion of the watershed. The locations diverged from this study's modeled findings that the impacts of the dam are greater in the upper part of the watershed.

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RECOMMENDATIONS

DECEMBER 2022

RECOMMENDATIONS

DECEMBER 2022

SUPPORT THE REGION 8, LOWER BRAZOS REGIONAL FLOOD PLANNING DRAFT PLAN

This study supports the draft recommendations of the Region 8 Flood Planning Group to comprehensively address flooding from a regional perspective and develop regionwide floodplain management goals and standards.[1]

This study supports the draft Legislative Recommendations of the Region 8 Flood Planning Group to provide additional state funding for improvements to flood data collection, drainage studies, and local ordinances, and to update local authority to regulate floodwaters.[2]

Future regional flood planning cycles should proactively identify more sponsors in the Navasota River watershed to support the numerous planning studies and mitigation activities, including various debris removal projects and drainage master studies, that were collected as suggestions during the current flood planning process but not adopted in this planning cycle.

LOWER BRAZOS REGIONAL FLOOD PLANNING GROUP'S DRAFT REGIONAL FLOODPLAIN GOALS (JULY 2022)

1. Increase the number of counties and communities enrolled in the National Flood Insurance Program (NFIP).
2. Increase the number of counties and communities that have adopted higher than NFIP standards, including directing development away from the floodplain.
3. Increase the number of entities that have adopted the best available data and science for their designs and plans.
4. Improve safety at low water crossings by adding warning systems/signage or improving low water crossings in high-risk areas.
5. Reduce the number of structures that are in the 100-year floodplain by both structural (flood infrastructure) and non-structural (elevation, acquisition, relocation, etc.) means.
6. Reduce the number of critical facilities at risk of flooding during the 100-year rainfall event to above the 500-year rainfall event by both structural (flood infrastructure) and non-structural (elevation, buy-outs, relocation, etc.) means.
7. Increase the accuracy of flood hazard data in the region by performing detailed studies using the best available terrain, land use, and precipitation data to reduce gaps in floodplain mapping.
8. Increase the number of communities with warning and emergency response programs that can detect flood threats and provide timely warning of impending flood danger.
9. Increase the number of flood gauges (rainfall, stream, reservoir, etc.) in the region.
10. Increase public outreach and education activities to improve awareness of flood hazards and the benefits of flood planning in the region.[3]

RECOMMENDATIONS

DECEMBER 2022

CLARIFY DEBRIS MANAGEMENT PROGRAMS & FUNDING

The Texas Department of Transportation (TxDOT) and appropriate local infrastructure agencies should evaluate major bridge structures crossing the Navasota River for debris blockages and potential removal.

Given the importance of bridge crossings to flood mitigation activities, the Texas Water Development Board should consider adding additional representatives from road and bridge infrastructure organizations (such as TxDOT and local governments) to Regional Flood Planning Group compositions.

In future flood planning cycles, the regional flood planning process should more comprehensively address regional debris removal needs, document the responsible jurisdictions for debris removal, and suggest a process for funding and maintaining debris removal programs for mitigation purposes.

The state and federal government should consider funding regional debris removal programs as a mitigation strategy and clarify eligible entities to carry out the work.

IMPROVE STAKEHOLDER COMMUNICATIONS DOWNSTREAM OF LAKE LIMESTONE

The Brazos River Authority (BRA) should conduct additional stakeholder outreach and develop communications specific to their roles and responsibilities and those of other entities along the river, including in topics of water supply, flood control, and debris removal.

The BRA should develop communications and stakeholder outreach specific to the communities below Lake Limestone to directly address questions regarding the operation of the dam and continue to improve transparency and relationships with these communities.

EMBRACE MULTI-PRONGED, WATERSHED-LEVEL FLOOD RESILIENCE STRATEGIES

The regional flood planning process should continue to embrace a multi-pronged approach to flood mitigation. In the future, the planning process should consider using and building upon the Institute for a Disaster Resilient Texas' "avoid, resist, accommodate, and communicate" framework adopted by the Commission to Rebuild Texas following Hurricane Harvey.[4]

RESILIENT FLOOD MITIGATION FRAMEWORK

AVOID

Removing development or steering it away from vulnerable areas.

- Elevate (fill or piers)
- Open space protection
- Buy-outs/land acquisition
- Relocation
- Buffers/setbacks
- Incentivize development
  - Transfer of development rights
  - Density bonuses
  - Tax incentives
- Spatially targeted development

RESIST

Preventing the intrusion of flood waters into human settlements.

- Construction of natural features
- Flood-proof residential and non-residential structures
- Strengthen development standards
- Stormwater diversions
- Bioengineered bank stabilization
- Floodwalls or small berms
- Water gates & subsurface drainage systems

ACCOMODATE

Allowing flooding in specific areas or under certain conditions.

- Detention/retention
- Storm drainage
- Wetland protection/ restoration
- Break-away walls
- Ponds/swales
- Conduct regular maintenance of stormwater infrastructure
- Improve existing stormwater drainage capacity

COMMUNICATE

Providing ongoing flood and storm risk information to residents.

- Disclosure
- Regional watershed planning
- Interagency partnerships
- Technical assistance programs
- Promotion of flood control incentive programs
- Web tools/apps
- Research/studies

COLLECT ADDITIONAL DATA AND CONDUCT STUDIES TO MONITOR THE NAVASOTA RIVER OVER TIME

The BRA, in coordination with the U.S. Geological Survey (USGS) and other appropriate local jurisdictions, should consider funding the placement of additional gauges downstream of Lake Limestone to support more robust monitoring and analysis of flooding in localized downstream areas. Placement of additional rain gauges would provide improved coverage and spatial distribution within the watershed. Stream gauge placement should focus on locations that see significant runoff or discharge (e.g., channel/tributary confluences) and/ or prioritize locations that are known to be flood-prone (e.g., inundation hotspots) or have experienced repetitive flood loss. Data from rain gauges could be used to correct any bias from radar-based rainfall data, and stream gauges could be used to help calibrate and/or validate modeling results. More importantly, the gauges could be used to better monitor the stream conditions during severe storm/dam release events and aid in decision-making and/ or emergency response measures.

Future regional flood planning cycles should support additional studies that:

- Evaluate the causes and impacts of geomorphic changes and erosion on flooding along the Navasota River.
- Analyze a broader range of historical rainfall events to fully understand how flooding and flood duration changes across storm types.
- Collect additional bathymetric data to better determine the river's water storage capacity and assess how it changes over time.
- Fly low-altitude crewed aircraft to comprehensively map the entire Navasota River watershed to begin collecting high resolution elevation data, channel structure, and building footprints to help understand future implications of flooding.
- Conduct a soil infiltration study to better understand soil characteristics and moisture conditions of the study area to improve the accuracy of hydrologic and hydraulic modeling efforts.
- Conduct a study that explicitly addresses how pre-releases from the Sterling C. Robertson dam on Lake Limestone would or would not influence downstream flooding. Such a study should analyze the range of costs and benefits associated with the impacts on both water supply and flood impacts and the high level of uncertainty with determining these tradeoffs. The study should also illustrate how such measures could potentially reduce water supply and increase downstream flooding during events such as Hurricane Harvey in which pre-releases would have been recommended but ultimately unnecessary since little to no rain occurred upstream of the reservoir.

FURTHER DEVELOP MULTIDISCIPLINARY FLOOD EVALUATION METHODS

The use of unmanned aerial vehicles (drones) to investigate potential flood mitigation opportunities, coordination of multiple modeling techniques, and integration of social science methods to rapidly assess localized flooding concerns were innovations of this study. Regularly coordinating with the regional flood planning process throughout the study also helped ensure the research could contribute to the state's planning process. The Institute and partner organizations should further develop these multidisciplinary flood impact and assessment methods to improve this type of research in the future and continue to contribute to the regional flood planning process as funding allows.

ENDNOTES

1 Region 8 Regional Flood Planning Group. (2022) Draft Chapter 3: Floodplain Management Practices and Flood Protection Goals. *Region 8 – Draft 2023 Lower Brazos Regional Flood Plan.* https://lowerbrazosflood.org/Portals/5/PlanningDocuments/Draft-2023-Report/Report%20Chapters/Ch3_Floodplain%20Management%20Practices%20and%20Flood%20Protection%20Goals.pdf

2 Region 8 Regional Flood Planning Group. (2022) Draft Chapter 8: Administrative, Regulatory, and Legisla-tive Recommendations. *Region 8 – Draft 2023 Lower Brazos Regional Flood Plan*. https://lowerbrazosflood.org/Portals/5/PlanningDocuments/Draft-2023-Re-port/Report%20Chapters/Ch8_Administrative%20Regulatory%20and%20Legislative%20Recommendations.pdf

3 Region 8 Regional Flood Planning Group. (2022) Draft Chapter 3: Floodplain Management Practices and Flood Protection Goals. *Region 8 – Draft 2023 Lower Brazos Regional Flood Plan,* Table 3.5, pp. 3-21. https://lowerbrazosflood.org/Portals/5/PlanningDocuments/Draft-2023-Report/Report%20Chapters/Ch3_Floodplain%20Management%20Practices%20and%20Flood%20Protection%20Goals.pdf

4 The Governor's Commission to Rebuild Texas. (2018). Chapter 7: Building a More Resilient Texas. *Eye of the Storm: Report of the Governor's Commission to Rebuild Texas.* https://gov.texas.gov/uploads/files/press/RebuildTexasHurricaneHarveyEyeOfTheStorm_12132018.pdf

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NAVASOTA RIVER
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