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Comparing floodplain evolution in channelized and unchannelized urban watersheds in Houston, Texas

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Abstract

In this study, we compare the ability of two riverine flood control approaches: channelization and stream preservation/setbacks, to alleviate the adverse impacts of rapid urbanization. To study the effects of structural intervention and urban development on the evolution of the floodplain, we have chosen two neighboring urban watersheds in Houston, TX: Brays Bayou and Buffalo Bayou. While the two watersheds are similar in size, topography, and development level, they have contrasting riverine flood management approaches. Brays Bayou is channelized, whereas Buffalo Bayou remains mostly unchannelized. We use the distributed hydrologic model, Vflo®, and the hydraulic model, HEC-RAS, to analyze channel hydraulics and floodplain extent in the two watersheds under the 10- and 100-year rainfall scenarios at three points in time: 1970s (early development), 2011 (current development), and 2040 (future development). We find that, while floodplain extent in both watersheds increases over time, the relative change in floodplain extent for Brays Bayou (channelized) is substantially larger than that for Buffalo Bayou (unchannelized). The results in this study contribute to a better understanding of the long-term performance of two flood mitigation approaches (channelization and setbacks) on riverine flood risk and provide insight into best management practices for cities experiencing rapid urban growth.

KEYWORDS

channelization, distributed hydrologic modeling, flood risk management, floodplain, HEC-RAS, land use/land cover change, urbanization, Vflo®

1 | INTRODUCTION

Throughout the 1800s and early 1900s, large-scale flood control structures (e.g., dams, levees, channels) dominated flood control policy and floodplain management in the United States (Birkland, Burby, Conrad, Cortner, & Michener, 2003; NRC, 2013). However, since the 1960s, U.S. flood policy has also incorporated nonstructural

measures such as flood insurance, more stringent drainage criteria, and building codes to mitigate flood risk (Tarlock, 2012). While the integration of structural and nonstructural measures should be expected to encourage sustainable floodplain management, the payouts from the Federal Emergency Management Agency's (FEMA) National Flood Insurance Program (NFIP) have increasingly exceeded the revenue generated through insurance

premiums, resulting in annual deficits since 2005 (Sebastian & Gori, 2018). By the end of 2016, the NFIP's total debt exceeded $20 billion (FEMA, 2016; GAO, 2009).

To increase long-term urban resilience to floods, it is crucial to better understand the performance of different floodplain management approaches and their impact on the spatial extent and depth of the floodplain at the watershed scale. For this analysis, we define the floodplain as the area inundated due to the overtopping of channel banks from a given design storm, for example, the 10- or the 100-year SCS Type III rainfall. While many studies have focused on the environmental costs of channelization and its impacts on watershed hydrology (Little Inc, 1973; Rose & Peters, 2001; Schoof, 1980), few have explicitly analyzed its contribution to the floodplain relative to long-term urbanization changes (Habete & Ferreira, 2017; Suriya & Mudgal, 2012). Moreover, to our knowledge, previous studies have yet to consider how different riverine management approaches perform under nonstationary land use conditions or their combined impact on floodplain evolution. In this paper, we compare the evolution of the floodplain in two neighboring watersheds: Brays Bayou and Buffalo Bayou, located in Houston, Texas, in which contrasting flood management strategies have been implemented (Figure 1). Brays Bayou was fully channelized in the 1960s, whereas the main channel in Buffalo Bayou has been left largely in its natural state. The watersheds are similar in size and topography, and development patterns across the two watersheds are comparable. Recent flood events have exposed the vulnerability of midstream communities (located between the upstream [US] and downstream [DS] gauges shown in Figure 1) in Brays Bayou watershed to severe flooding (compared to Buffalo Bayou), raising questions about the effects of the two different riverine management strategies on the evolution of risk in the two watersheds.

In the following section, we discuss one of the most common flood control practices in the United States, channelization, and describe previous research related to its performance in urbanizing watersheds. Additionally, we provide a short history of the two watersheds and discuss flood management practices in the context of urban flooding. In Section 3, we present the methods and models used in this study. The results and discussion are presented in Section 4. Finally, in Section 5, we present concluding remarks and recommendations for future research.

2 | BACKGROUND

Channel modifications, collectively referred to as channelization, are intended to increase the carrying capacity of a natural stream. Channelization is especially prevalent in the south and southeastern United States, where low topographic relief leads to wide and shallow floodplains. By structurally altering one or more of the hydraulic variables that govern channel flow (e.g., slope, depth, width, roughness), velocities in the channel are increased and the height of water decreased. The primary advantage of lowering the depth of water in the channel is that it reduces the size (i.e., spatial extent) of the floodplain, allowing for economic development and growth in previously flood-prone areas.

Supporters of channelization have often touted its local flood risk reduction benefits; however, many studies
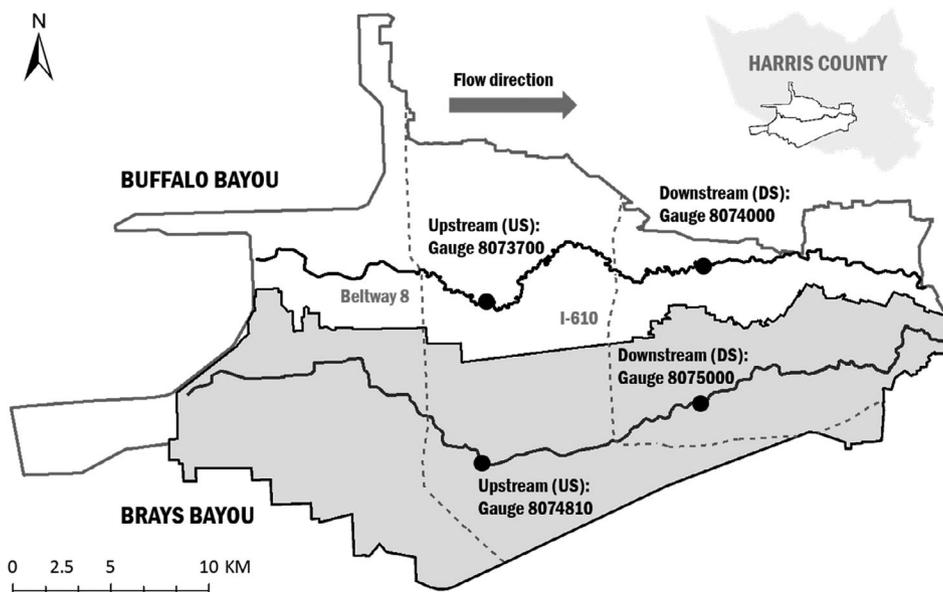
FIGURE 1 Brays Bayou and Buffalo Bayou watersheds, with watch point (gauge) location

have also shown that channelization can also have unintended consequences in other parts of the watershed, especially in DS communities (Booth, 1991; Prestegaard et al., 1994; Rose & Peters, 2001; Shankman & Samson, 1991). For example, Prestegaard et al. (1994) found that areas DS of a modified channel section of Raccoon River, Iowa, had experienced higher-magnitude floods compared to similarly sized areas US. Likewise, Rose and Peters (2001) showed that channel improvements increase the flood wave velocity, thereby decreasing peak timing DS. Others have focused primarily on the negative effects of channelization on water quality (Schoof, 1980). For example, widespread channelization has contributed to higher rates of nonpoint source pollution in receiving bodies of water. Channel modifications have also been shown to affect temperature (i.e., thermal pollution), sediment transport, and natural flood regimes of urban streams, permanently altering the ecology of the stream and the riparian corridor (Holman-Dodds, Bradley, & Potter, 2003).

Early studies promoting structural measures for flood risk reduction often neglected to consider the development encouraged in protected areas perceived to be safe (Burby, 2001; White, 2010; Wright, 2000). Especially in the southeastern United States where channelization has been implemented to minimize floodplain extent and to allow for development, urban sprawl, characterized by vast swaths of impervious cover, has contributed to increases in runoff volume. The conventional method for managing this increase in runoff is to route it via channels, pipes, and culverts into the main channel (Burns, Fletcher, Walsh, Ladson, & Hatt, 2012; Dietz, 2007; Hood, Clausen, & Warner, 2007). Nevertheless, as development in the watershed increases and pervious surfaces decrease, runoff volume may eventually exceed channel capacity due to development practices that fail to fully offset their flood impacts, thereby resulting in higher flood damages than in the undeveloped scenario. This creates a cycle of demand in which continued investment in structural flood control is required to maintain the same level of protection in existing communities (Hale, 2009).

2.1 | Study area

Harris County, located on the upper Texas Gulf Coast, encompasses the majority of the City of Houston and the surrounding metropolitan areas. The region is extremely vulnerable to flooding due to its flat topography, low-infiltration capacity soils, high rates of impervious cover, and subtropical climate that is prone to both hurricanes and severe storms. Harris County has one of the highest

rates of repetitive flood losses and flood-related fatalities in the United States. Furthermore, a large percentage of damages in Harris County occur outside of the mapped regulatory floodplain areas (Highfield, Norman, & Brody, 2013). As of June 30, 2017, the total insured losses that have been paid out in Harris County exceeded $3 billion USD (FEMA, 2017).

Buffalo and Brays Bayous are two of the primary drainage basins for the City of Houston (Figure 1). Together, they drain nearly 596 km² (230 mi²), flowing eastward before converging near the Houston Ship Channel just east of downtown. These two bayous are rainfall-fed and, consequently, carry negligible base flow; however, during rain events, these bayous serve as the primary drainage mechanism for their respective watersheds and thus can experience extremely high peak flows. They account for two of the most heavily developed watersheds in the region. While similar in many physical aspects, the governing flood management practices in the two watersheds differ significantly. Table 1 summarizes the physical characteristics of the two watersheds, and Figure 2 shows schematics of the riverine management strategies implemented at each watershed.

2.1.1 | Brays Bayou (channelized)

Brays Bayou has a contributing drainage area of 332 km² (128 mi²) and an estimated population of more than 717,198 people (Harris County Flood Control District [HCFCD, 2017a]). In response to heavy storms in the first half of the 20th century, Brays Bayou was largely channelized by the U.S. Army Corps of Engineers (USACE) in partnership with the Harris County Flood Control District (HCFCD). The project, completed in 1968, resulted

TABLE 1 Brays Bayou and Buffalo Bayou watershed characteristics

Characteristic	Brays	Buffalo
Area (km²)	332	264
Main channel length (km)	51	47
Average channel bed slope	0.0006	0.0005
Gravelius shape coefficient (GC)[a]	1.8	3
Soil type	Clay, clay loam, loam	Clay, clay loam, loam

[a]GC is the ratio of a catchment's perimeter to the circumference of a circle with an area equivalent to the basin (GC = 1 denotes a perfectly circular basin).

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(a)

(b)
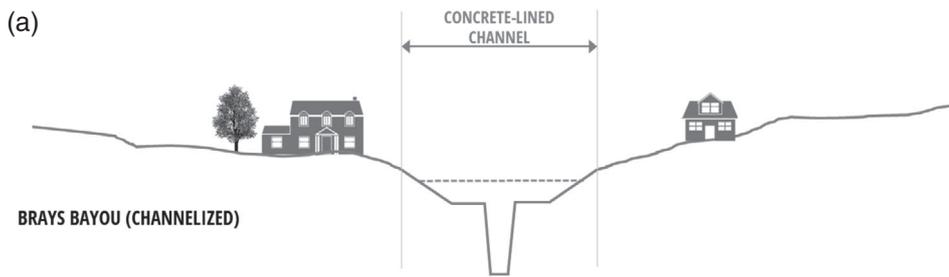
FIGURE 2 (a) Brays Bayou riverine management (channelized) schematic (Photo: Brays Bayou at Buffalo Speedway). (b) Buffalo Bayou riverine management (unchannelized) schematic (Photo: Buffalo Bayou near Waugh Dr.)
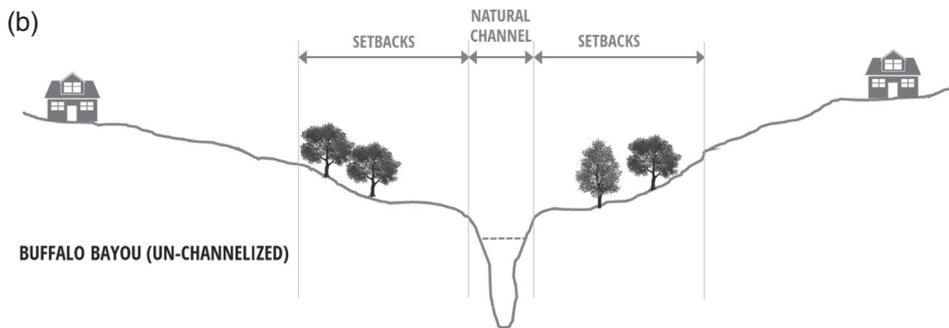
in 40.9 km (25.4 mi) of channel improvements (i.-e., widening and deepening the main channel) and 22 km (13.7 mi) of concrete-lined channel DS of US-59 (HCFCD, 1998). At the time, the channel improvements were designed to provide enough capacity to handle the 100-year flows associated with a fully developed watershed (Bass, Juan, Gori, Fang, & Bedient, 2017); however, modeling tools to accurately measure the effects of urbanization had not yet been developed (HCFCD, 1998).

By the 1980s, it became clear that Brays Bayou had grown increasingly prone to flooding during extreme precipitation events. In an effort to relieve the pressure on local communities, the HCFCD and USACE undertook a 20-year, $550 million project: Project Brays (HCFCD and USACE, 2015). Project Brays added additional storage (through detention) in the US portion of the watershed, raised bridges and removed their piers from the water, and widened the channel. However, recent events have highlighted the continued vulnerability of local communities to heavy precipitation events despite the improvements provided by Project Brays (Bass et al., 2017).

2.1.2 | Buffalo Bayou (unchannelized)

In contrast, Buffalo Bayou has been largely preserved in its natural state.[1] In response to channelization in Brays and other adjacent watersheds, the Bayou Preservation Association (BPA) was formed in 1967 as an advocacy group to protest against channelization of Buffalo Bayou and promote nature-based flood management strategies for Houston's watersheds. The BPA together with George H. W. Bush—then a local congressman—successfully halted further structural interventions along Buffalo Bayou, thus allowing the majority of the bayou to remain in its natural state. Today, Buffalo Bayou remains one of the few natural riparian waterways in Houston, draining approximately 264 km^2 (102 mi^2). Much of the upper portion of Buffalo Bayou flows through heavily wooded residential areas, and urban parks in the DS portion have helped maintain open space and setbacks from the channel. Significant investments have recently been made to renovate the parks along the DS portion of Buffalo Bayou and increase recreational use and valuation of the historic waterway. The watershed has an estimated population of more than 444,602 people (HCFCD, 2017b).

3 | RESEARCH METHODS

This study uses a distributed hydrologic model, Vflo$^®$, and 1D steady hydraulic model, Hydrologic Engineering Center-River Analysis System (HEC-RAS), to model the flood hazard in Brays Bayou and Buffalo Bayou watersheds. After validating the Vflo$^®$ model for the current development conditions against design storm results from the official models used by the HCFCD, gridded land use/land cover (LULC) data were imported into Vflo$^®$ to analyze the evolution of the 10- and 100-year floodplains across the three development scenarios. For the purpose of this study, historical, current, and future LULC data were collected and preprocessed in ArcGIS for the 1970s

(historical), 2011 (current), and 2040 (future) watershed conditions for both watersheds.

The following sections provide a brief overview of the hydrologic model used in this study, describe the model setup and validation process, and then discuss the collection and processing of LULC data to represent different development scenarios.

3.1 | Hydrologic model: Vflo$^®$

Vflo$^®$ is a physics-based, fully distributed hydrologic model that solves the conservation of mass and momentum equations using a finite-element approach (Vieux, Bralts, Segerlind, & Wallace, 1990; Vieux, Cui, & Gaur, 2004). In Vflo$^®$, the watershed domain is represented as a grid in which each cell contains parameters that account for elevation, soil type, and land cover. Rainfall runoff calculations are performed for each cell in the model domain, with overland runoff routed via the Kinematic Wave Analogy (KWA) and channel routing using the Modified Puls method. A full description of the Vflo$^®$ model formulation and derivation of the KWA is documented in Vieux and Vieux (2002).

While regulatory floodplains have traditionally been modeled utilizing lumped hydrologic models, such as HEC-HMS, distributed models have the unique ability to represent spatially diverse soil and land cover characteristics and thus provide a more accurate representation of the physical parameters of the watershed. For this reason, Vflo$^®$ is a powerful tool for modeling the cumulative impacts of land cover changes in this study. Vflo$^®$ has been used and validated in numerous studies throughout the Houston region (Vieux & Bedient, 2004, Fang et al., 2010, Doubleday, Sebastian, Luttenschlager, & Bedient, 2013, Torres et al., 2015, Juan, Hughes, Fang, & Bedient, 2017, Blessing, Sebastian, & Brody, 2017, Gori et al. 2019, Sebastian, Gori, Blessing, van der Wiel, & Bass, 2019).

3.2 | Hydraulic model: HEC-RAS

To model the riverine floodplains associated with the 10- and 100-year rainfall events, the HEC-RAS software, developed by the USACE, was used. HEC-RAS is used for a wide range of applications, such as floodplain assessment, flood insurance studies, and dam breach analysis (Hydrologic Engineering Center, 2016). The 1D steady-state model serves as the basis for generating FEMA floodplains used for floodplain management and policy in the United States. The model generates a static water surface profile (i.e., maximum water surface elevation) along the entire channel based on peak discharges

inputted at specific channel cross sections. In this study, the effective hydraulic models of Brays Bayou and Buffalo Bayou developed by HCFCD, obtained from the Model and Map Management (M3) system (HCFCD, 2017c), were used to investigate the influence of urban development on the riverine flood hazard that occurs when water spills over the channel banks into the urban environment.

3.3 | Model setup

This study focuses on the middle section of both Brays Bayou and Buffalo Bayou watersheds (between the US and DS watch points shown in Figure 1), where residential and commercial developments are the primary land uses. The middle section of Brays, in particular, has been subject to severe riverine flooding in recent years (Bass et al., 2017). Developed Vflo® models for Brays and Buffalo Bayou watersheds have grid cell resolutions of 91 m (300 ft). Both models are run using a 5-min timestep. In order to represent LULC characteristics in Vflo®, land use categories were converted to Manning's roughness and percent impervious. Using LULC categories from the National Land Cover Database (NLCD), associated roughness values were derived from Kalyanapu, Burian, and McPherson (2009), and impervious values were taken from NLCD guidelines. Besides roughness and imperviousness, Vflo® also requires elevation and soil data; 2008 LiDAR elevation data were obtained from the Houston-Galveston Area Council (HGAC) at 5 m resolution for both watersheds to develop the overland flow direction grid and extract channel cross sections of the bayou. Infiltration is modeled using the Green and Ampt Equation, which requires parameters of hydraulic conductivity, wetting front capillary pressure head, effective porosity, and soil depth. Soil data were obtained from the Texas Natural Resources Information System (TNRIS) and infiltration parameters referenced from Rawls, Brakensiek, & Miller, 1983. The Vflo® models only simulate surface runoff for the watersheds and exclude any underground storm sewer pipes. This simplification is justified as the storm sewer network in is are only designed to carry flow from a 2-year rainfall event (Sreerama & Varshney, 2017). Thus, for extreme rainfall events, the impact of the storm sewer network is negligible.

3.4 | LULC scenarios

In this study, a set of Vflo® models that represent specific periods of land use conditions for each watershed was developed. To capture a range of development conditions for both watersheds, LULC data were collected at three points in time: 1970s (historical), 2011 (current), and 2040 (future). Historical LULC was obtained from the United States Geological Survey (USGS) as a polygon shapefile with minimum polygon sizes ranging from 4 to 16 ha. The polygons were derived from high-resolution aerial photographs from NASA and the National High-Altitude Photography program. The source photographs span a time frame from 1970 to 1985 and are meant to represent LULC for the 1970s (Price, Nakagaki, Hitt, & Clawges, 2006).

Current LULC for the year 2011 was also collected from the USGS through the NLCD. The source of this data comes from Landsat 5 Thematic Mapper imagery, and Landsat images were taken from the USGS Earth Resources Observation and Science Center. The 2011 land use data were obtained as a raster dataset with 30 m resolution.

Land use data for future conditions (2040) were obtained from HGAC. These land use data are produced by HGAC models that utilize population and employment projections to estimate the demand for housing units and commercial space and then determine which existing land parcels are likely to be developed (Houston-Galveston Area Council, 2016). Both historical and future land use data were processed to match the NLCD LULC categories in order to derive roughness and imperviousness values. Aside from their roughness and imperviousness values, the three Vflo® models for each watershed are identical.

3.5 | Model validation

As the 2040 (future) models represent projected development conditions, model validation was performed for only the 1970s (historical) and 2011 (current) models. For the 1970s LULC scenario, modelled peak flows were validated against observed data from five storms that occurred between 1967 and 1973, resulting in R^2 values of 0.89 for Brays Bayou and 0.81 for Buffalo Bayou. More detailed information regarding the validation for the 1970s model and the storm events is included in Appendix A.

For the 2011 scenario, modelled Vflo® discharges were compared against observed flow data at corresponding USGS gauge locations. The models were validated against recent storm events: the Memorial Day 2015 Storm (May 26–27, 2015) for both watersheds and the Tax Day 2016 Storm (April 18–19, 2016) in the Buffalo Bayou watershed and a May 26, 2016 storm event in Brays Bayou. These storms caused substantial flooding across the region. Figures 3 and 4 shows the Memorial Day 2015 validation results for both watersheds. The full-

model validation results are available in Appendix B. Overall, Vflo® closely reproduced the peak flow, timing, and shape of the flow hydrographs when compared against observed data. Average Nash-Sutcliffe Efficiency (NSE) values are 0.87 in Brays and 0.90 in Buffalo for the Memorial Day 2015 Storm, 0.70 in Brays for the May 2016 storm, and 0.87 in Buffalo for the Tax Day 2016 Storm. These results demonstrate that the Vflo® models represent the current hydrologic responses of both watersheds for these storm events well.

After successful validation of the Vflo® models, hydrograph output from the 10- and 100-year design rainfall events is used as input to the official 1D steady-state HEC-RAS model, and maximum 10- and 100-year water surface elevations are computed for each land use scenario. The design storms simulated in this study were 24-hr duration, SCS Type III rainfall hyetographs outlined in the 2009 Hydrology and Hydraulics Guidance Manual published by HCFCD. For both watersheds, a 10-year storm equates to 19.3 cm (7.6 in.) in 24 hrs, and a 100-year storm equates to 33.5 cm (13.2 in.) in 24 hrs. Floodplains for each land use scenario are generated from computed water surface elevations and elevation data (2008 LiDAR).

4 | RESULTS AND DISCUSSION

4.1 | Land use evolution

Figure 5 shows the evolution of development in each watershed from the 1970s to 2040, and Table 2 shows the percent development (i.e., low-intensity and high-intensity development) for each LULC scenario. Between the 1970s and 2011, both Brays and Buffalo Bayou watersheds experienced a substantial increase in the extent of developed land, while projections for 2040 depict greater urban densification due to more widespread high-intensity development.

Next, a spatial analysis of the stream corridors in the two bayous based on current LULC conditions was performed to better understand the development patterns in the riparian zones extending 100 m on both sides of the channels' banks. The 2011 LULC classes were simplified into three categories: natural (e.g., forest, grassland, wetland, etc.), open space (i.e., developed green space), and developed (e.g., residential, commercial, etc.). Based on these classes, the riparian corridor in the middle section of the Buffalo Bayou was found to contain 23% natural and 40% open space (63% undeveloped), whereas the middle section of Brays was found to contain only 5% natural and 13% open space (18% undeveloped), with over 82% developed land adjacent to the stream. This analysis shows that Buffalo Bayou's setback approach has left a substantial portion of land adjacent to the stream in its natural state and allocated open space along the banks to serve as a buffer against flooding. In contrast, residential and commercial development in the Brays Bayou watershed has encroached the edge of the stream with limited buffer space.

4.2 | Streamflow responses

To effectively compare streamflow responses between the two watersheds, modeled discharges at two watch points in each watershed (US and DS) were normalized by their corresponding contributing drainage areas. This metric is necessary because, while the distance of each watch points from the outlet of each watershed is fairly similar, the contributing drainage areas to those watch points differ. Figures 6 and 7 show modeled normalized 10- and 100-year stream flows under three development scenarios at Brays Bayou and Buffalo Bayou. Table 3 summarizes the normalized modeled peak flows for both watersheds, whereas Table 4 lists the percentages of normalized peak flow increases for the 1970s–2011 and 2011–2040 periods.
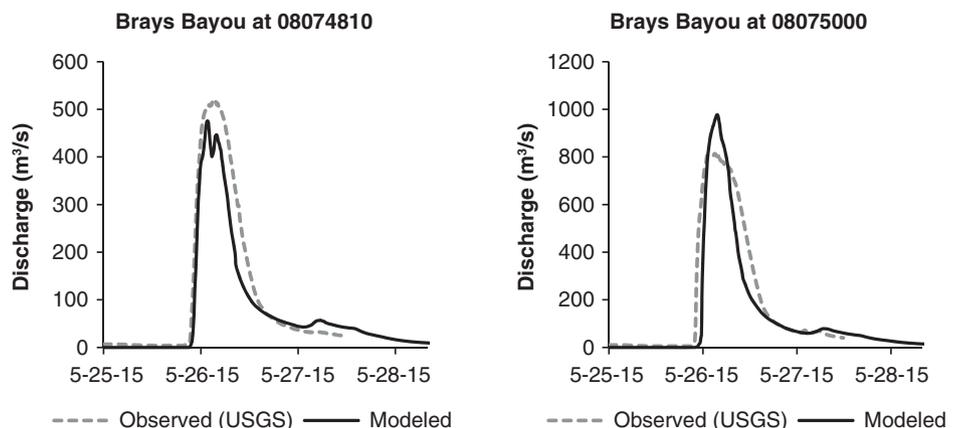
FIGURE 3 Stream flow comparisons for the Memorial Day 2015 Storm in Brays Bayou
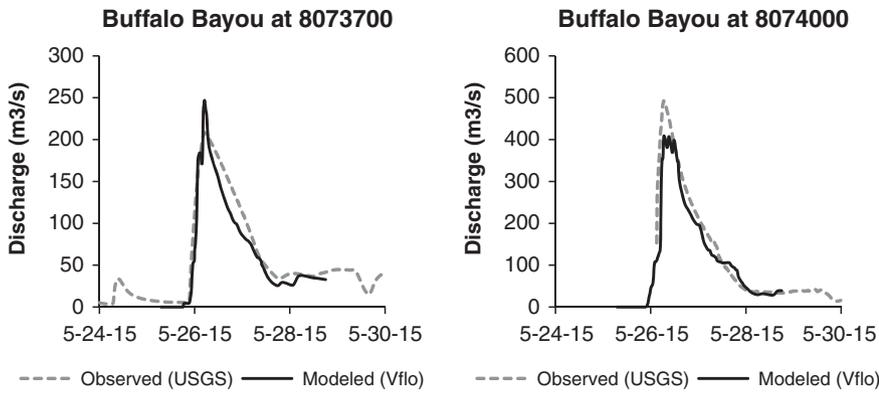
FIGURE 4 Stream flow comparisons for the Memorial Day 2015 Storm in Buffalo Bayou
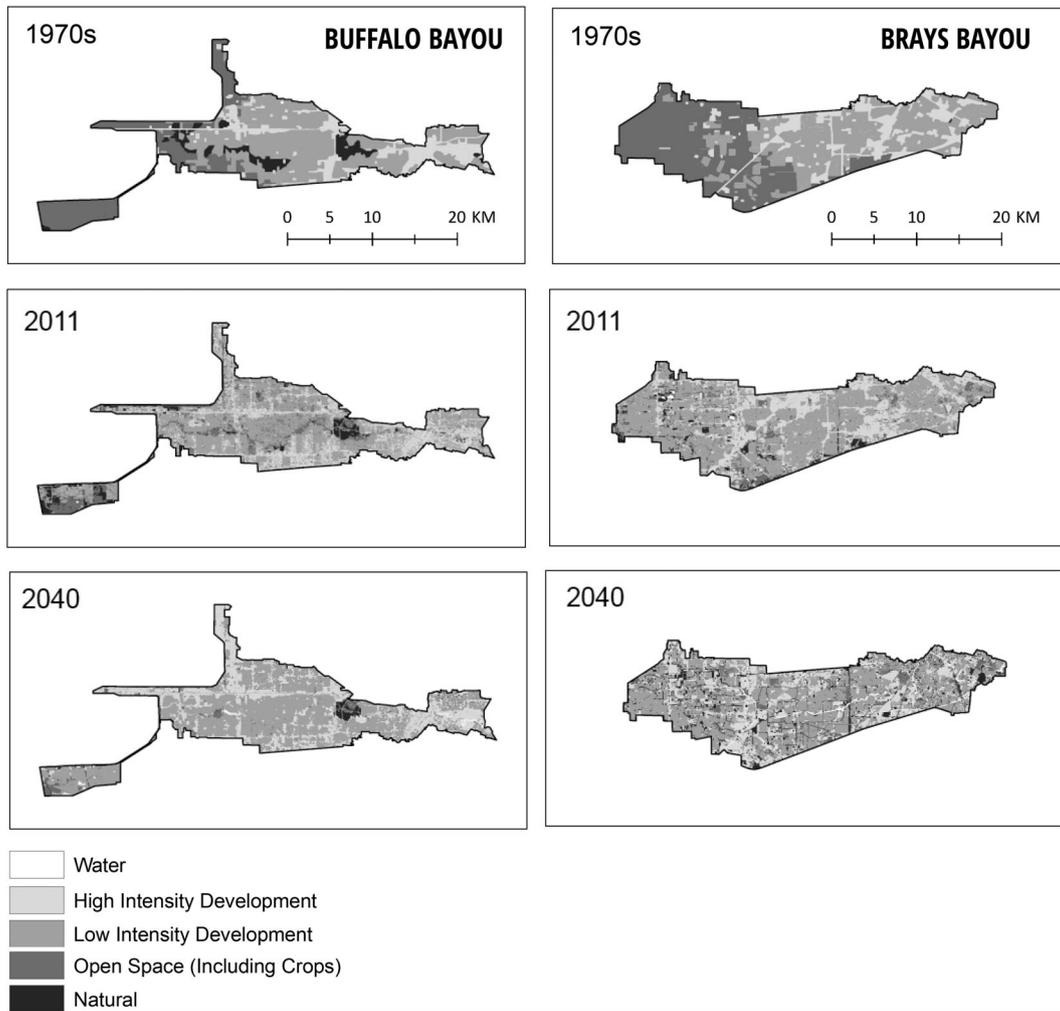
FIGURE 5 Land use evolution for Brays (channelized) and Buffalo Bayou (unchannelized) watersheds

Between the two watersheds, Brays Bayou generally shows higher normalized peak flows compared to Buffalo Bayou at corresponding watch points for all scenarios (Table 3), with one notable exception. At the US watch points for the 1970s scenario, Buffalo Bayou shows higher normalized peak flows compared to Brays Bayou (1.76 vs. 1.30 cms/km^2 for the 10-year flow and 4.10 vs. 2.75 cms/km^2 for the 100-year flow), which indicates that Buffalo Bayou had more upstream development in the 1970s. Next, Table 3 shows that, for all LULC and storm scenarios, Brays Bayou sees an increasing trend of normalized peak flows from its US to DS watch points. Conversely, Buffalo Bayou actually sees a decreasing trend in normalized flows from its US to DS watch

points. These results suggest that Buffalo Bayou's riverine management strategy helped absorb the impacts of US runoff.

When examining the watersheds individually, Brays Bayou's US watch point (Gauge 8074810) indicates that both 10- and 100-year normalized peak flows have nearly doubled between the 1970s and 2011 (115% for the 10-year and 89% for the 100-year flows). Moreover, the time of concentration, t_c, has decreased significantly, as evidenced by the 2011 hydrographs having flashier (peakier) hydrologic responses compared to the 1970s hydrographs (Figure 6). Similarly, the DS watch point (Gauge 8075000) also shows some increase in normalized peak flows during this period, although not to the same extent seen at the US location (24% for the 10-year and 21% for the 100-year

flows). However, unlike at the US watch point, t_c at this location remains relatively constant. We hypothesize that this is because, by 1970, the DS portion of Brays Bayou watershed has already been developed, while the US portion remained mostly undeveloped (see Figure 5). Thus, the effects of urban development (e.g., change in imperviousness and overland roughness) between the 1970s and 2011 are more pronounced at the US section of the watershed, which consequently resulted in a greater jump in normalized peak flows and decrease in t_c. These results agree with findings from a recent study by Sebastian et al., 2019, in which the authors found that flood flows during Hurricane Harvey (2017) at gauges in the Brays Bayou watershed have more than doubled since the 1900s due to urbanization and channelization and that these increases are much larger than at any other gauges in the Houston region.

In the same manner, only a slight increase in normalized peak flows and no significant changes in t_c are observed between the 2011 and the projected 2040 development scenarios. These results are unsurprising because, by 2011, the entire Brays Bayou watershed had been almost entirely developed (Figure 5), and the projected LULC changes between 2011 and 2040 mostly indicate that there will be an intensification of low- and medium-intensity development to medium- and high-intensity development, rather than the conversion from undeveloped to developed areas. Because of this, the change in impervious cover and overland roughness is less substantial compared to that of the previous period,

TABLE 2 Percent development of Brays and Buffalo watersheds (% increase since the 1970s)

		1970s	2011	2040
Brays	Low intensity	41.0	61.7	49.1
	High intensity	16.1	24.8	37.5
	Total dev. % change	—	(29%)	(29%)
Buffalo	Low intensity	49.6	55.2	40.0
	High intensity	14.8	26.0	42.5
	Total dev. % change	—	(17%)	(18%)

Note: The relatively minor change in total percent development between 2011 and 2040 is due to intensification of development rather than the conversion of undeveloped spaces to developed.
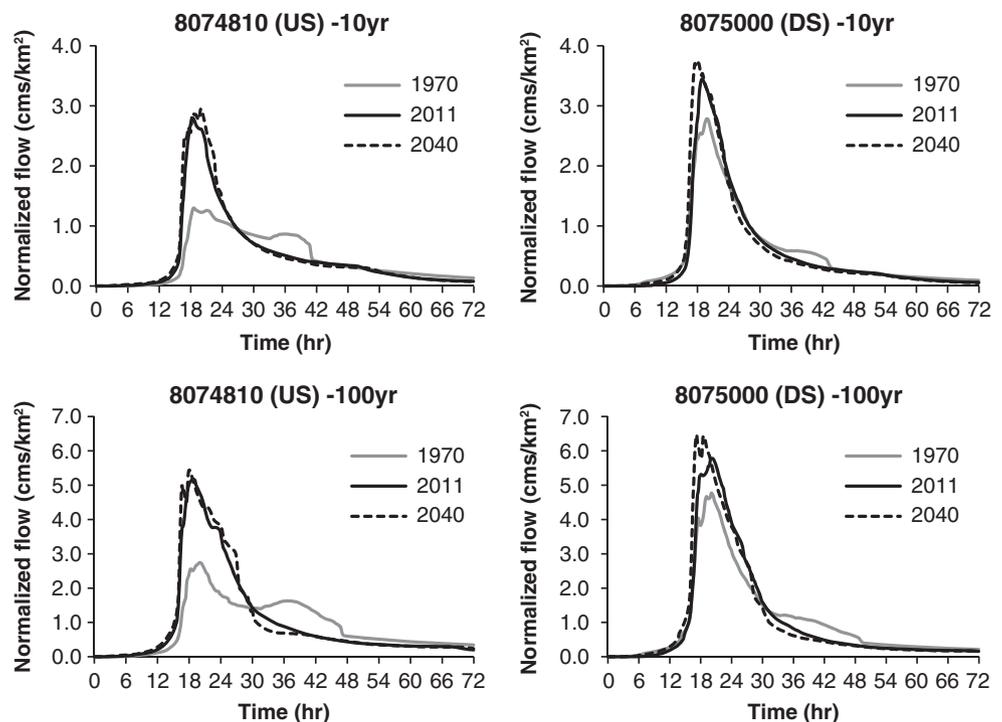
FIGURE 6 Modeled normalized streamflow (cms/km^2) for Brays Bayou under three LULC scenarios (US drainage area: 120.6 km^2, DS drainage area: 219.5 km^2)
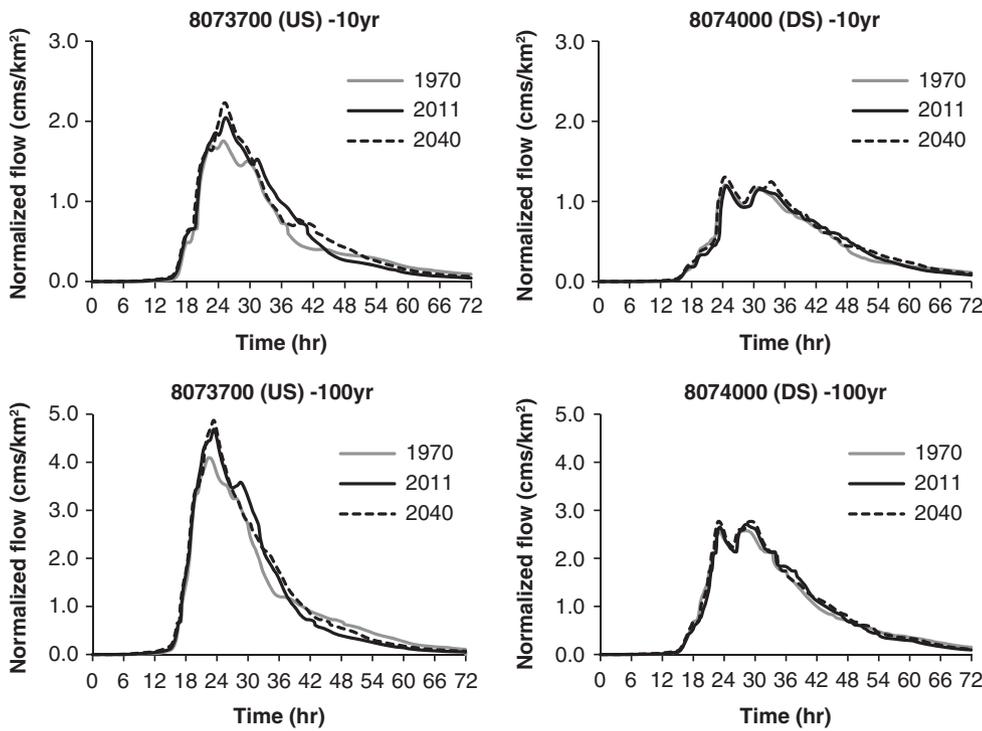
FIGURE 7 Modeled normalized streamflow (cms/km²) for Buffalo Bayou under three LULC scenarios (US drainage area: 73.9 km², DS drainage area: 181.0 km²)

TABLE 3 Modeled normalized peak flows (cms/km²) for 3 LULC scenarios

| | Brays | | | | Buffalo | | | |
| | 10 year | | 100 year | | 10 year | | 100 year | |
	US	DS	US	DS	US	DS	US	DS
1970s	1.30	2.79	2.75	4.77	1.76	1.20	4.10	2.58
2011	2.79	3.45	5.18	5.78	2.05	1.20	4.69	2.71
2040	2.95	3.71	5.44	6.47	2.23	1.30	4.87	2.77

Abbreviations: DS, downstream watch point/gauge; US, upstream watch point/gauge.

TABLE 4 Normalized peak flow increase (%) for the 1970s–2011 and 2011–2040 periods

| | Brays | | | | Buffalo | | | |
| | 10 year | | 100 year | | 10 year | | 100 year | |
	US	DS	US	DS	US	DS	US	DS
1970s–2011	115%	24%	89%	21%	17%	1%	14%	5%
2011–2040	6%	8%	5%	12%	9%	8%	4%	2%

Abbreviations: DS, downstream watch point/gauge; US, upstream watch point/gauge.

which corresponded to a less substantial change in normalized peak flows and almost no change in *tc*.

In contrast to Brays, Buffalo Bayou experiences no significant changes in streamflow response under the three development scenarios at either its US (Gauge 8073700) or DS (Gauge 8074000) watch points. For the 1970s–2011 period, there is an increase in normalized peak flow at the US watch point of 17% for the 10-year storm and 14% for the 100-year storm. At the DS watch point, the increases are only 1% for the 10-year storm and 5% for the 100-year storm. For the 2011–2040 period, the normalized peak flow at the US watch point in Buffalo Bayou increases by 9% for the 10-year storm and 4% for the 100-year storm. At the DS watch point, increases were only 8% for the 10-year storm and 2% for the 100-year storm. The *tc* changes during these periods are negligible (Figure 7). These results are notable because, as with Brays, the Buffalo Bayou watershed experienced

rapid development between the 1970s and 2011, with only minor changes in development between 2011 and 2040 (see Table 2). Despite this, the hydrologic responses in the two watersheds are noticeably different.

Aside from the difference in riverine management strategies, there are two likely factors that might contribute to the differences in streamflow response between the two watersheds. First, the Brays Bayou watershed experienced substantially higher development change during the 1970s–2011 period when compared to Buffalo (i.e., 29 vs. 17%), which means that Brays is likely to experience a correspondingly higher increase in urban runoff compared to Buffalo. While the higher rate of development change in Brays is a valid concern, it does not fully account for the dramatic change in normalized peak flows between the two watersheds for the 1970s–2011 period (see Table 4), nor does it explain the fact that Buffalo Bayou's DS watch point has lower normalized peak flow values compared to its US watch point (Table 3).

The second probable factor is that Buffalo Bayou inherently has a higher storage and conveyance capacity compared to Brays Bayou. In the past, the bayou drained not only the current extent of Buffalo Bayou watershed but both the Addicks and Barker Reservoir watersheds as well. As Addicks and Barker now operate as separate systems (both reservoirs are designed to remain closed except during the most extreme events), the contributing drainage area was significantly reduced, while the bayou's capacity remained constant. Despite this, the measurement of channel widths through aerial imagery at several locations of interest demonstrated that both channels actually have similar widths (approximately 35 m); however, Buffalo Bayou has wide swaths of low-lying natural, vegetated areas that extend far beyond both sides of its banks when compared to Brays, providing additional flood storage and conveyance. Most of these low-lying areas have remained free from residential and commercial development as demonstrated in the stream corridor spatial analysis discussed previously. Toward the mid and DS sections of Buffalo, these vegetated areas are either preserved in their natural state or repurposed as developed green spaces (e.g., parks). Hence, Buffalo Bayou's high storage and conveyance are due to the combined capacities of both its main channel and its extensive low-lying overbank areas, rather than the capacities of the channel by itself.

4.3 | Floodplain extent

Results in the previous section clearly demonstrate that Buffalo Bayou, with its natural drainage and setbacks, is considerably more successful in absorbing the impacts of increased urban runoff compared to Brays Bayou. This

TABLE 5 Floodplain extent (km²) under three LULC scenarios for Brays and Buffalo watersheds

	10-year			100-year		
	1970s	2011	2040	1970s	2011	2040
Brays	4.92	6.45	6.60	10.5	46.1	73.3
Buffalo	5.35	5.71	5.83	8.50	9.64	9.90

finding is further corroborated in the comparison of modeled floodplains for the two watersheds. The 10- and 100-year floodplain extents under all three development scenarios for Brays and Buffalo Bayou watersheds are listed in Table 5, and the modeled 100-year floodplains are shown in Figure 8. For the 10-year storm, Brays Bayou's increase in flooding extent is nearly proportional to its percent increase in development under corresponding LULC periods (e.g., a 29% increase in percent development during the 1970s–2011 period resulted in a 31% increase in floodplain extent). For the same storm in Buffalo Bayou, the percent increase in floodplain is significantly lower than the percent increase in development (e.g., a 17% increase in percent development during the 1970s–2011 period only resulted in a 7% increase in floodplain extent). While Brays Bayou's increase in floodplain extent is significantly larger than that of Buffalo Bayou's, modeled floodplains show that each channel is generally able to contain the 10-year storm within its banks under all three development scenarios.

One area in the midstream section of Brays Bayou is of particular interest. This section, known as Meyerland, is one of the most flood-prone neighborhoods in Harris County and has flooded repeatedly during recent storms (i.e., Memorial Day 2015, Tax Day 2016, and Hurricane Harvey 2017). The flood vulnerability of Meyerland, and Brays Bayou watershed as a whole, is obvious when one examines the modeled floodplains for Brays. For the 100-year storm, the Brays Bayou watershed shows a fourfold increase in floodplain extent in 2011 when compared to the 1970s and a further 230% increase for the projected 2040 scenario, with most of the increase occurring at Meyerland.

In contrast, Buffalo Bayou shows almost no discernable differences in floodplain extent across all three development scenarios. The 100-year floodplain extent in 2011 increases by approximately 13% compared to the 1970s floodplain and another 3% for its projected 2040 floodplain. The differences in floodplain extent between these two watersheds are striking. Brays Bayou has struggled to contain a 100-year storm even when the watershed was relatively undeveloped in the 1970s. Meanwhile, not only can Buffalo Bayou easily contain a
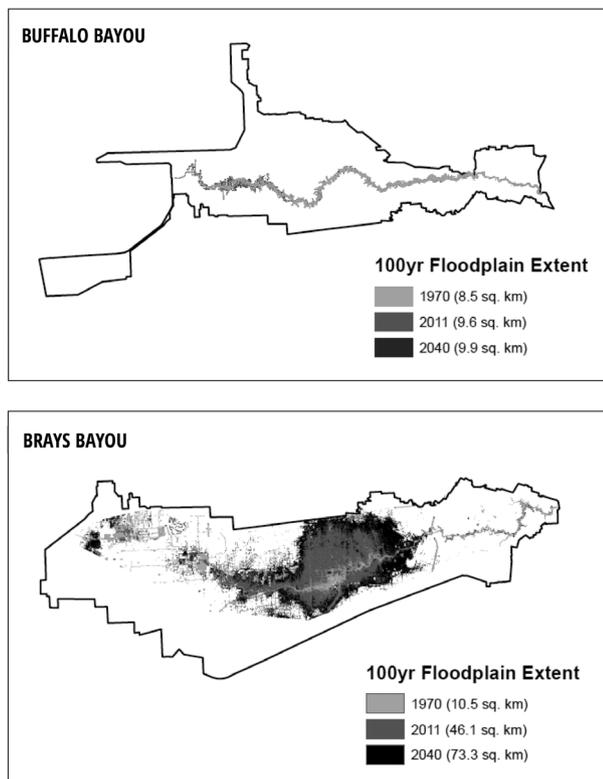
FIGURE 8 Modeled floodplains for Buffalo Bayou (unchannelized) and Brays Bayou (channelized) under three LULC scenarios

100-year storm under current development condition (i.e., 2011 LULC), it is also shown that it will be able to withstand the same storm under its projected 2040 development conditions. Similar results were also observed in a recent study (Gori, Blessing, Juan, Brody, & Bedient, 2019) that examined evolving land use impacts on a rapidly urbanizing watershed (Cypress Creek watershed in northwest Houston), in which the authors found that the lower portion of the channel that has been left in its natural state experiences less increase in floodplain extent under future land use conditions.

A closer examination of the modeled 100-year floodplains and selected cross sections under the 2011 LULC condition demonstrate that both Brays and Buffalo Bayous actually overtopped their channel banks, but while the spillover water from Brays immediately flooded the surrounding vicinity, Buffalo Bayou's spillover only flooded its larger riparian corridor, thereby limiting the extent of inundation significantly (see Figures 9 and 10). This observation has important implications as, from a flood risk perspective, the residents who reside within the Buffalo Bayou watershed have a much lower probability of inundation compared to those in Brays Bayou.

To illustrate this sentiment, the number of residential parcels within the 100-year floodplain modeled under the

three development scenarios for both watersheds are compared. As Table 6 shows, the number of residential parcels within the 100-year floodplain in the 1970s' LULC is quite similar for both watersheds (534 for Brays and 495 for Buffalo). By 2011, however, Brays had a staggering 24,227 parcels within its 100-year floodplain, compared to a mere 725 at Buffalo. By 2040, Brays is projected to have more than 37,000 parcels within its 100-year floodplain, compared to 839 at Buffalo. These results clearly indicate the difference in level of flood exposure and potential flood damages in the two watersheds. We attribute the low number of residential parcels within the modeled floodplains in Buffalo Bayou in part to the decision that prevents residential development from occurring near the stream; had it been otherwise, flood risk and flood damage would most certainly be much higher.

5 | CONCLUSIONS

The comparison between Brays and Buffalo Bayou's flood management strategies shows that Buffalo Bayou's strategy, consisting of mostly natural drainage and setbacks, is more successful at minimizing the adverse impacts of urban development on riverine flooding over time despite similar rates and intensity of urban development. Together with the natural channel, the setbacks function as a riparian buffer that delays urban runoff, attenuating streamflow and subsequently alleviating DS flow accumulation. These setbacks also provide additional flood storage if and when the channel overtops its banks, thus preventing water from immediately flooding surrounding communities. Moreover, as recent studies have found that the region is subject to increases in extreme precipitation from urbanization and climate change (Emanuel, 2017; Risser & Wehner, 2017; van Oldenborgh et al., 2017; Zhang, Villarini, Vecchi, & Smith, 2018), this strategy is likely to be more resilient to future changes in extreme rainfall induced by climate change (Sebastian et al., 2019) and to be better at offsetting future flood risks. Finally, the results also indicate that the natural system's capacity to adapt to changing LULC is greater than that of a fully engineered system.

One downside of applying such a flood management strategy postdevelopment is that, depending on the necessary flood storage capacity, the required setback areas needed may be quite extensive. In many fully urbanized watersheds such as Brays Bayou, this option would simply be infeasible. At the very least, the implementation of setbacks at this point in the watershed's development might require some politically, economically, and/or logistically challenging maneuvers such as large-scale property buyouts to convert flood-vulnerable properties

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FIGURE 9 100-year floodplain with selected cross-sectional (XS) view at Brays Bayou
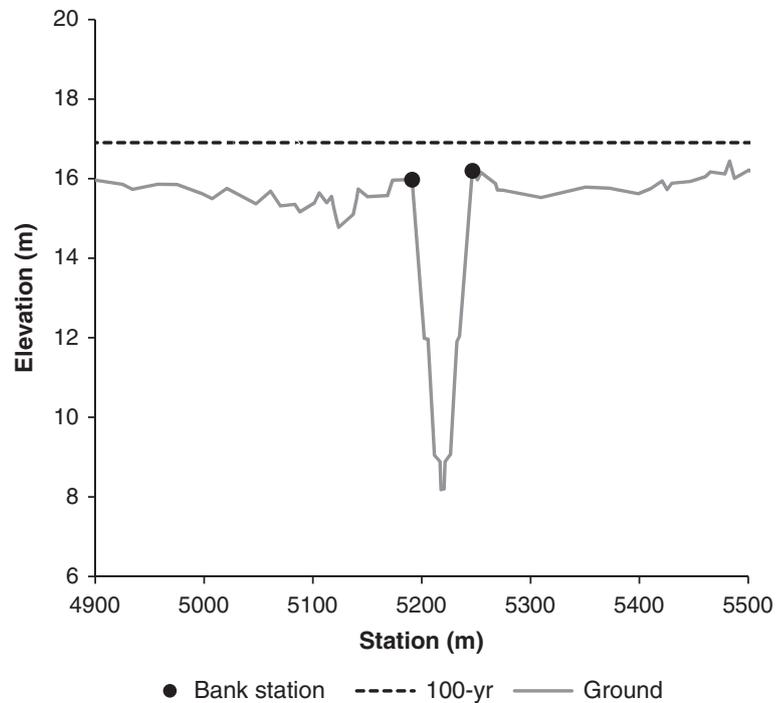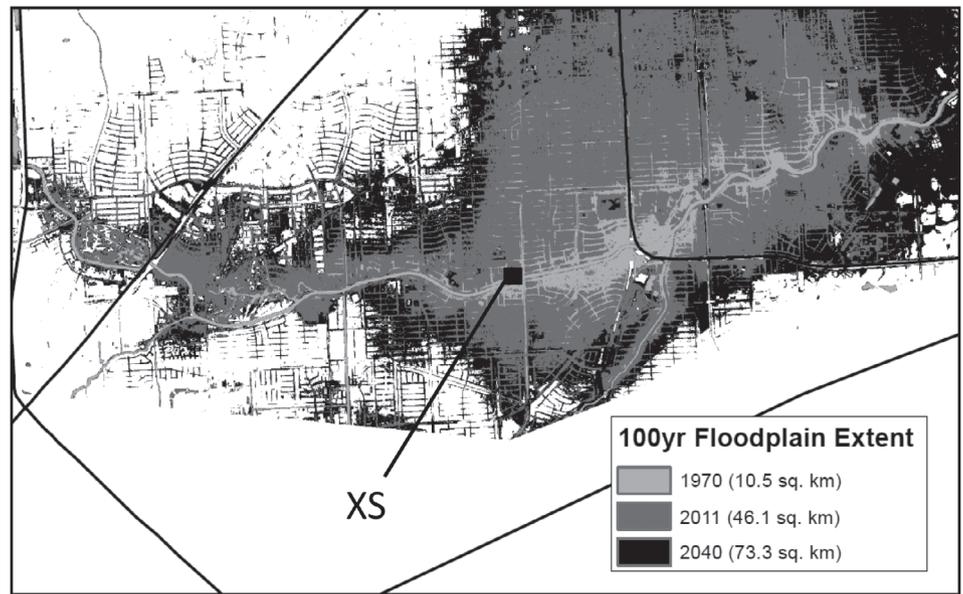
to setbacks or detention areas. This suggests that natural riverine management options would need to be pursued *ex-ante* and would be difficult to implement as a retrofit strategy for an urbanized watershed.

A potentially more sensible approach for fully urbanized watersheds, Brays Bayou specifically, is to repurpose existing green spaces such as parks and golf courses to serve as additional flood detention areas. These new detention and flood storage facilities would need to be built and placed strategically to protect the most flood-prone areas (Fang et al., 2010). For watersheds that are becoming increasingly urban but are not yet fully developed, previous studies have indicated that the preservation of open space and native land cover can provide the necessary flood storage to offset the negative effects of urban development (Brody, Blessing, Sebastian, & Bedient, 2014; Doubleday et al., 2013; Juan et al., 2017). Engineered green spaces such as golf courses, parks, and various green infrastructure practices could also be utilized to provide additional flood storage when properly designed. While the cost and logistics could still pose an issue, it would be arguably more feasible than buying out residences along the entire stretch of the bayou and reconditioning them as setbacks.

The primary goal of this study was to better understand how contrasting riverine management strategies
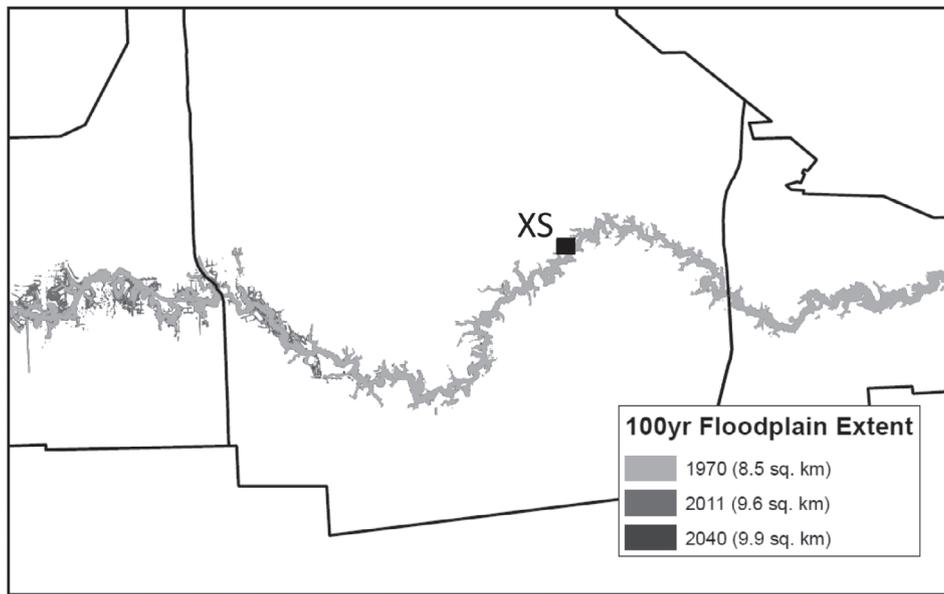
FIGURE 10 100-year floodplain with selected cross-sectional (XS) view at Buffalo Bayou
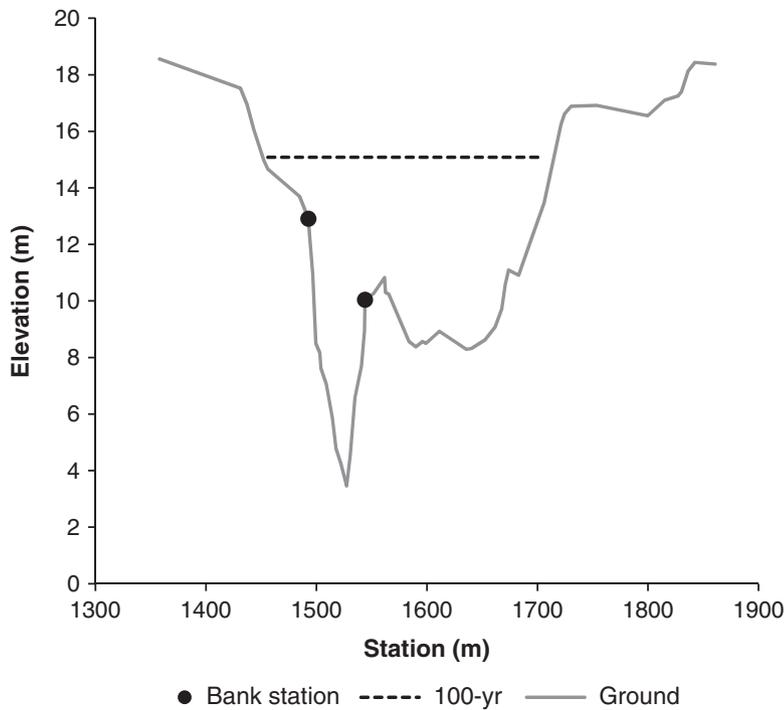
TABLE 6 Number of residential parcels within modeled 100-year floodplains for Brays Bayou and Buffalo Bayou watersheds

	1970s	2011	2040
Brays	534	24,227	37,012
Buffalo	495	725	839

affect streamflow response in rapidly urbanizing watersheds; thus, several simplifying assumptions were made at the onset and should be noted. First, we only considered the contribution of rainfall to flood flows in the two watersheds. In other words, any source of runoff from outside of the watershed boundary, such as water releases from US reservoirs or interbasin transfers, were not considered. In Buffalo Bayou, this means that both the potential backwater effects from the confluence with White Oak Bayou and the releases from the US Addicks and Barker reservoirs were excluded. This is a reasonable assumption as the water stored behind the reservoirs is not typically released until after flood events. Recent events have highlighted the importance of these reservoirs to flood risk in Buffalo Bayou, and future analyses should also consider flood risk in the two watersheds

driven by larger storms to better understand the long-term performance of aging flood infrastructure. Second, regional detention ponds and diversions are present within each watershed. However, because they influence streamflow response, they were excluded from the study. This holds true especially for Brays Bayou, where several US detention basins have been built as part of Project Brays to alleviate DS flooding (Bass et al., 2017). Finally, this study applied the same elevation dataset (i.e., 2008 LIDAR) for all three LULC periods to exclude subsidence as a possible driver to changes in the modeled floodplains. We acknowledge, however, that resource withdrawal has contributed to significant subsidence in the region (The Harris-Galveston Coastal Subsidence District, 2014) and that future research should examine how local subsidence has contributed to differences in flood risk in the two watersheds.

Ultimately, this study demonstrates that urbanization impacts on floodplain extent for the channelized Brays Bayou far exceeds that of the mostly natural Buffalo Bayou. These results can help city officials, urban planners, floodplain managers, and various other stakeholders plan for more effective and resilient flood risk management strategies, which take into consideration urban development and its long-term flood impacts.

AUTHOR CONTRIBUTIONS

A.J. and A.S. conceived and designed the study. A.J. and A.G. built the models and prepared the results. All authors drafted and revised the manuscript and gave final approval for publication.

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ENDNOTE

[1] In the 1940s, two large dams were built in the US portion of the watershed: Addicks in 1948 and Barker in 1945, and 9.7 km (6 miles) of the channel between Addicks Reservoir and Beltway 8 were straightened by the USACE to protect downtown Houston from flooding; however, for comparison purposes, the area US of the two reservoirs is not considered part of the Buffalo Bayou watershed in this paper.

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APPENDIX A: | Model validation for the historical (1970s) scenarios

To validate the historical (1970s) Brays and Buffalo hydrologic models, we compared the two 1970s models against measured peak flows at five USGS gauges: 8073500, 8073600, 8073700, 8074000, and 8075000, across five flood events that occurred between 1967 and 1973: September 1967, February 1969, October 1970, March 1972, and June 1973. These events represented the highest peak flows in each year and resulted in 19 points of historical observations for comparison. Time-variable storm hydrographs were not available for these events. For each event, we collected hourly precipitation at all available observation stations in the greater Houston region using NOAA's Climatic Data Center Climate Data Online platform. The models performed well across all five events, resulting in an R^2 value of 0.89 for both watersheds and R^2 values of 0.81 and 0.89 for Buffalo and Brays Bayous, respectively (Figure A1). It is important to note that, during the 1970s, there was only one observation gauge located in the Brays Watershed (8075000), resulting in only four points of comparison during the 1967–1973 time frame (Table A1).

APPENDIX B: | Model validation for the current (2011) scenarios

The current (2011) hydrologic models for Brays Bayou and Buffalo Bayou watersheds were validated against observed data recorded by several USGS gauges for two recent storms, Memorial Day 2015 (May 26–27, 2015) for both watersheds, Tax Day 2016 (April 18–19, 2016) for Buffalo Bayou, and a May 27, 2016 event for Brays Bayou. These storms caused widespread devastation for multiple watersheds in the Greater Houston region, with both Brays and Buffalo receiving 20–25 cm of rain within a 12-hr period. Precipitation data for this study's model validation were gauge-corrected QPE, which is a Multi-Radar/Multi-Sensor System product developed by the National Severe Storm Laboratory of NOAA. Overall, Vflo® was able to closely reproduce the peak flow, timing, and shape of the flow hydrographs compared to observed data. Average Nash-Sutcliffe Efficiency (NSE) values are 0.87 in Brays and 0.90 in Buffalo for the Memorial Day 2015 Storm, 0.70 in Brays for the May 2016 storm, and 0.87 in Buffalo for the Tax Day 2016 Storm. The following figures (B1 and B2) show model validations of the two watersheds for these storms.

TABLE A1 Table of maximum observed precipitation (cm) and observed peak discharge (cms) associated with five historic events recorded in the Brays and Buffalo Bayou watersheds between 1967 and 1973

Date of peak flow	Max. observed 48-hr precipitation (cm)	Peak observed discharge (cms)				
		8073500	8073600	8073700	8074000	8075000
09/21/1967	11.25	29.7	—	36.2	59.5	133.9
02/21/1969	9.40	65.1	—	68.5	83.0	261.6
10/11/1970	3.84	—	—	89.8	—	438.9
03/20/1972	13.11	84.1	106.8	106.5	260.5	—
06/13/1973	15.24	85.8	106.2	126.6	242.7	702.3

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1970s Model Validation
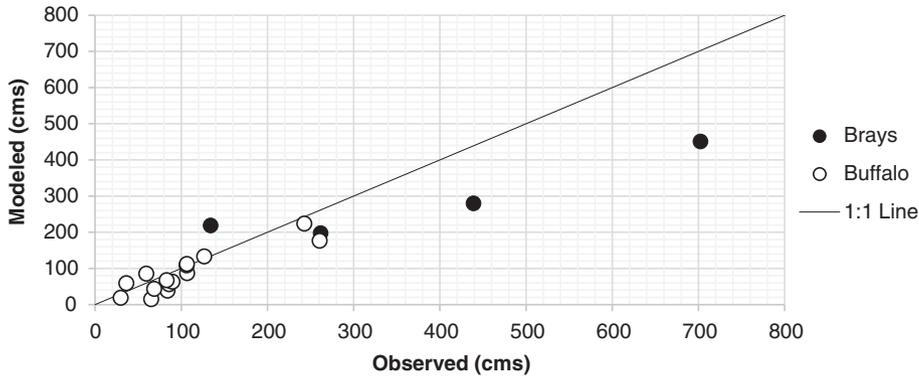
FIGURE A1 Model validation for the 1970s (historical) condition. Comparison between peak modeled and observed flows during five flood events (1967–1973) shown for gauges in Brays Bayou (solid) and Buffalo Bayou (open)
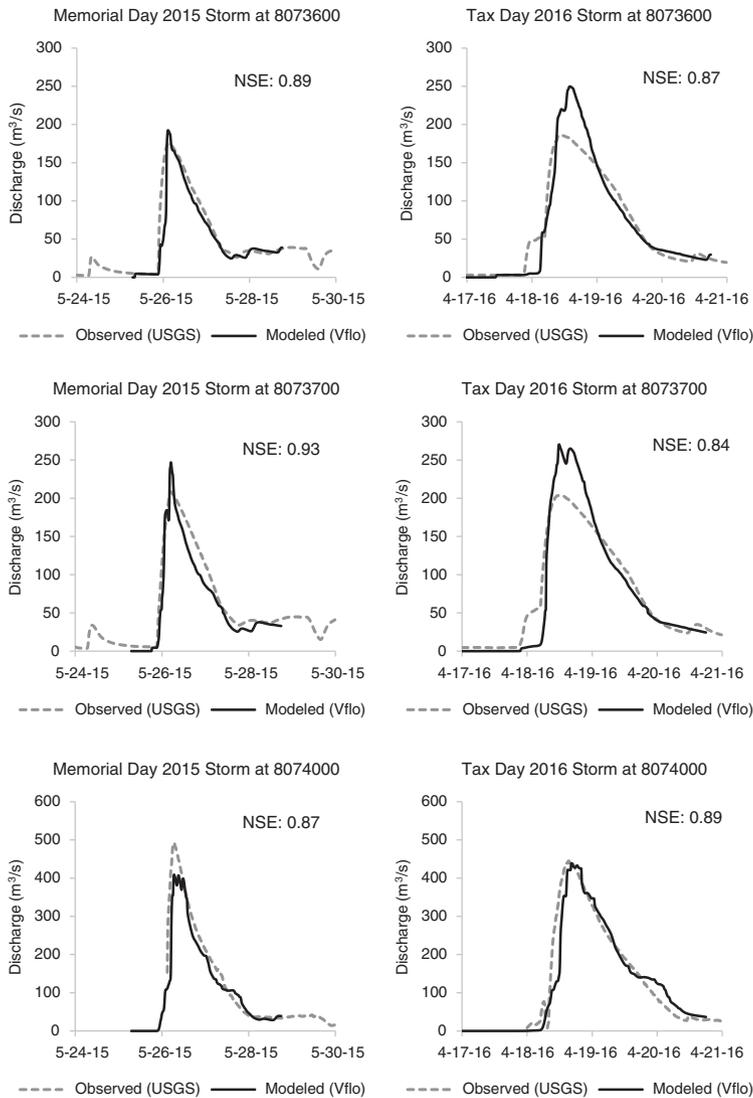
FIGURE B1 Stream flow comparisons in Buffalo Bayou

FIGURE B2 Stream flow comparisons in Brays Bayou