1 *Article*

# 2  From disaster to sustainability: breaking the cycle of
# 3  floods in Houston, Texas

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9   **Abstract:** The consequences of growing urbanization can be perceived in multiple levels around
10  the globe: overpopulated living conditions, water and air pollution, loss of open space, costly
11  transportation infrastructure, food shortages, fires and floods. The Houston metropolitan area is an
12  example of fast urban growth, with a population increase of more than sixteen percent in seven
13  years, going from 5.8 million people in 2010 to 6.9 million in 2017 [1]. By 2045, the robust growth of
14  the region is projected to lead to the addition of approximately five hundred square miles of
15  developed area, including an estimated six million parking spaces, seven hundred eighty million
16  square feet of non-residential uses, and three and a half billion square feet of residential use [2].
17  The accelerated development, in addition to physical features, geomorphic processes and human
18  activities in the region are believed to have caused Houston to suffer through over fifty devastating
19  floods since its settlement, despite some successful flood damage reduction projects. The present
20  study focused on the potential outcomes of an increased use of green infrastructure in comparable
21  urban areas, and its effects on flooding volume. Results from the research revealed that not only
22  these measures would likely improve the performance of existing urban drainage systems and
23  attenuate flood incidence in the area, but would also promote connectivity between areas
24  otherwise detached or only accessible by car, improving walkability and incentivizing engagement
25  in outdoor activities.

26  **Keywords:** flood; urban growth; development; land use/land cover; green infrastructure; drainage;
27  stormwater; runoff; underground storage

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## 29  1. Introduction

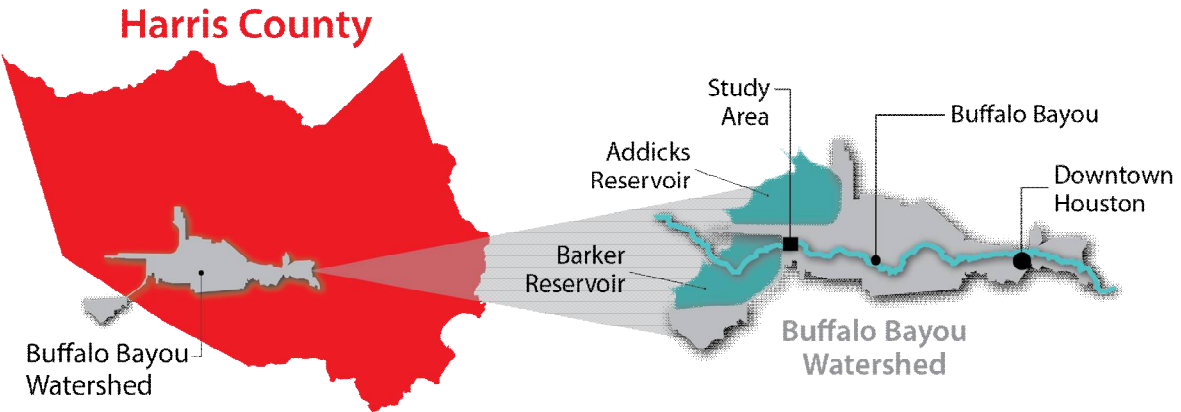
30      Houston is located in Southeast Texas near Galveston Bay and the Gulf of Mexico. It is the seat
31  of Harris County and the principal city of the Houston metropolitan area. The city has a total area of
32  approximately 601 square miles, and Greater Houston has a total area of 10,062 square miles,
33  according to the United States Census Bureau [3].
34      The city of Houston grew around the confluence of White Oak Bayou and Buffalo Bayou,
35  which served as a natural turning basin. The development spread east and west along Buffalo
36  Bayou, spurring at the turn of the century with the construction of the Houston Ship Channel [4],
37  and continued to grow through the twentieth century with the discovery of petroleum in the region.
38  Oil refineries proliferated along the Ship Channel placing Houston in the center of new oil and
39  oilfield equipment development, and in the 1920s the city saw its first growth spur. In the 1970s, the
40  Arab Oil Embargo caused the demand for Texas oil to escalate, attracting thousands of workers and
41  their families. [5]. As it is typical for a growing city, the strongest early growth in Houston was in the
42  core municipality and then gradually shifted to the nearby suburbs. Houston is suburban, and is
43  often characterized as a sprawling urban area, although it has a higher than average urban density if
44  compared to other cities with the same characteristics [6].

Flooding has always been endemic to Houston. From an environmental viewpoint, it is essential to understand that most of the Houston metropolitan area is nested inside a large bioregion of the Texas Gulf Coastal Plain, consisting of low elevations and nearly level to gently sloped soils that are poorly drained to moderately permeable. Downtown Houston stands about fifty feet above sea level and the entire city is relatively flat, with slopes ranging from zero to eight percent throughout the region, which makes stormwater drainage especially difficult. From an urban planning viewpoint, moreover, the vigorous growth experienced by the region in the last decades, associated with the unique ways the city has chosen to approach development regulation may have intensified the flood-prone characteristics of the place. The connection between the absence of zoning regulations and past flood events has been object of great debate, exacerbated after Hurricane Harvey's destructive flooding has impacted, directly or indirectly, most residents of Houston in August of 2017. Presumably, flood as result of a storm of that magnitude would have been catastrophic, despite the existence of zoning. Nonetheless, intensive building development has deforested and sealed areas that should otherwise be absorbing stormwater, and caused imbalance and transformation in their natural function as storage and conveyance system for water, nutrients and sediments [7].

**Figure 1.** Map of Texas and Harris County.       .

Harris County has classified 22 major watersheds that each drain into 22 major waterways. Buffalo Bayou watershed encompasses most of the study area and for this reason is particularly relevant to the research. This watershed is primarily located in west-central Harris County with a small portion crossing into Fort Bend County. Rainfall within the 102 square miles of the Buffalo Bayou watershed drains to the watershed's primary waterway, Buffalo Bayou - the longest and largest of the county's bayous, travelling 53 miles before meeting San Jacinto River at Galveston Bay. The Bayou is navigable as far as downtown Houston. Just east of downtown Houston near the Turning Basin, Buffalo Bayou becomes the Houston Ship Channel [8].

Few watersheds have garnered as much attention after Hurricane Harvey as the Addicks, Barker and Buffalo Bayou watersheds. Many neighborhoods upstream of the Addicks and Barker reservoirs flooded, and the releases from the dams placed sections of the area underwater for weeks. In many ways, however, this watershed is a success story. Large reservoirs at the upper end of watersheds can be highly effective, and the 75-year history of Addicks and Barker Reservoirs is an example. Until Hurricane Harvey, few homes flooded in the Buffalo Bayou watershed while neighborhoods along other bayous flooded repeatedly. A gradual reduction in the reservoirs' capacity (due to silt and vegetation) has reduced their effectiveness, but Buffalo Bayou still has significantly better flood protection than other watersheds [9]. Addicks and Barker reservoirs were built in the 1940s when Congress authorized the United States Army Corps of Engineers (USACE) to construct them as part of the Buffalo Bayou and Tributaries Project (BBTP). The reservoirs are located approximately seventeen miles from downtown Houston, and were designed to collect excessive amounts of rainfall to be released into Buffalo Bayou at a controlled rate. They fulfill their

84  purpose by impounding water during heavy rainfalls and flood events, but do not store water
85  year-round as it is typical of lake-forming reservoirs [10]. Under normal conditions, both dams have
86  two conduits set to pass the normal flow of water. When the reservoirs are empty and one inch of
87  rain falls below the dams, the gates are closed until it is safe to make releases. If releases are being
88  made, the gates will be closed if 0.5 inch of rain falls below the reservoirs or flooding is predicted.
89  Normal regulating procedures specify that releases from the two reservoirs, in addition to the
90  uncontrolled runoff downstream, should not exceed 2,000 cubic-feet per second (cfs) as measured at
91  the Piney Point Road gauging station. Addicks Dam has a maximum discharge capacity of 7,852 cfs
92  and Barker Dam 8,734 cfs [11]. Attempts to improve drainage and manage stormwater have lead
93  over time to alterations of the flows of nearly all of the Harris County bayous. Buffalo Bayou's
94  natural functions have been significantly altered by land development in the watershed, the
95  construction of Addicks and Barker reservoirs, and the deepening and widening of the bayou from
96  State Highway 6 to roughly Beltway 8/Rummel Creek. Despite these modifications, Buffalo Bayou is
97  a stressed natural stream in an urban environment [12].

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99
100  **Figure 2.** Location of Buffalo Bayou Watershed in Harris County.

101  **2. Materials and Methods**

102  Conventional city design has allowed society to thrive and grow in a range of challenging and
103  often uninhabitable environments. However, as global populations increase and shift from rural to
104  urban areas, the scale of urbanized regions is causing a stress surge on the natural environment and
105  its supporting systems. The natural water cycle is disrupted in urban areas because buildings,
106  concrete and other sealed surfaces prevent water from soaking into the ground. As a result, natural
107  water flows are altered, and excess stormwater is created, which is traditionally directed into local
108  waterways via drainage networks. This disruption to the natural water cycle causes many problems,
109  including pollution of waterways, bays and oceans; waterway erosion and degradation; urban
110  flooding; decreased soil moisture and reduced groundwater levels [13].
111  The core questions this research is proposing to explore include: How can flooding volume
112  reduction be achieved in the selected and similar areas? Would integration of green infrastructure
113  with existing flood control management and water resources significantly mitigate the flooding
114  problem? How can the existing built environment be reconciled with its surroundings to create a
115  cohesive landscape?

116  **The proposed approach can be subdivided into five phases:**

117  **Phase 1. Defining a Pilot Study Area**
118  A section of the Buffalo Bayou watershed containing 57 Census Block Groups and a surface
119  area of approximately 16.9 square miles was outlined as a "pilot study area" for the design model
120  being proposed. An initial approach considered the area adequate due to its proximity to Addicks
121  and Barker reservoirs, Terry Hershey Park, Buffalo Bayou and to the Energy Corridor, the

122    second-largest employment center in the region [14]. Most importantly, the selected area was one of
123    the most impacted during Hurricane Harvey. The underlying idea was to create a "prototype"
124    based on one of the most challenging sections of the study area that could be replicated, with the
125    appropriate adjustments, in comparable areas throughout the region.

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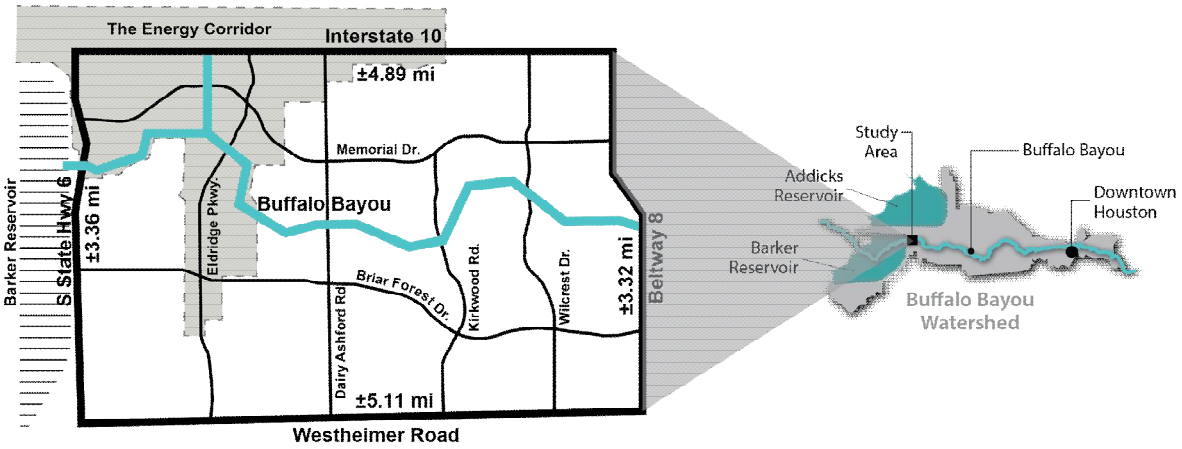
127          **Figure 3.** Outline of pilot study area for the proposed design model.

128          The pilot study area (Figures 3 and 4) is highly developed - approximately 90% - and densely
129    populated, and is a blend of residential land uses, intermixed with office, commercial,
130    public/institutional and industrial development, as Houston does not mandate the separation of
131    different land use categories. The majority of commercial and office structures is distributed along
132    Eldridge Parkway, Dairy Ashford Road, Memorial Drive and Interstate 10. The area has eleven
133    elementary schools, two middle schools, three high schools and ten private schools. Most of the
134    undeveloped land is composed of parks and open space for a total of 1,019 acres, 209 of which
135    belong to Lakeside Country Club, a private golf course, and approximately 500 to Terry Hershey
136    Park, a public pedestrian-friendly greenbelt. Buffalo Bayou crosses the entire study area from west
137    to east, and Terry Hershey Park runs along the Bayou for approximately six miles.

138    **Figure 4. Land use map of the pilot study area, generated in Geoplanner for ArcGis with GIS data from the**
139    **City of Houston.**

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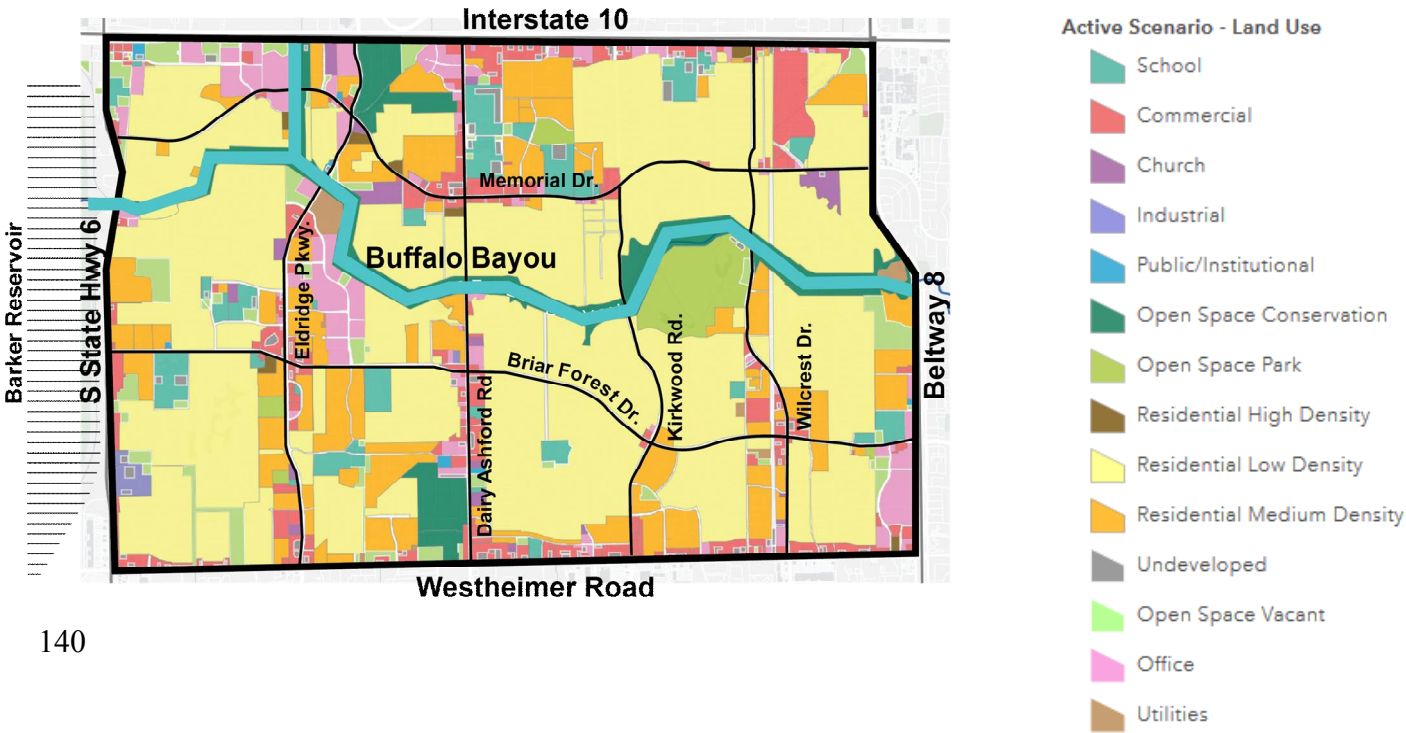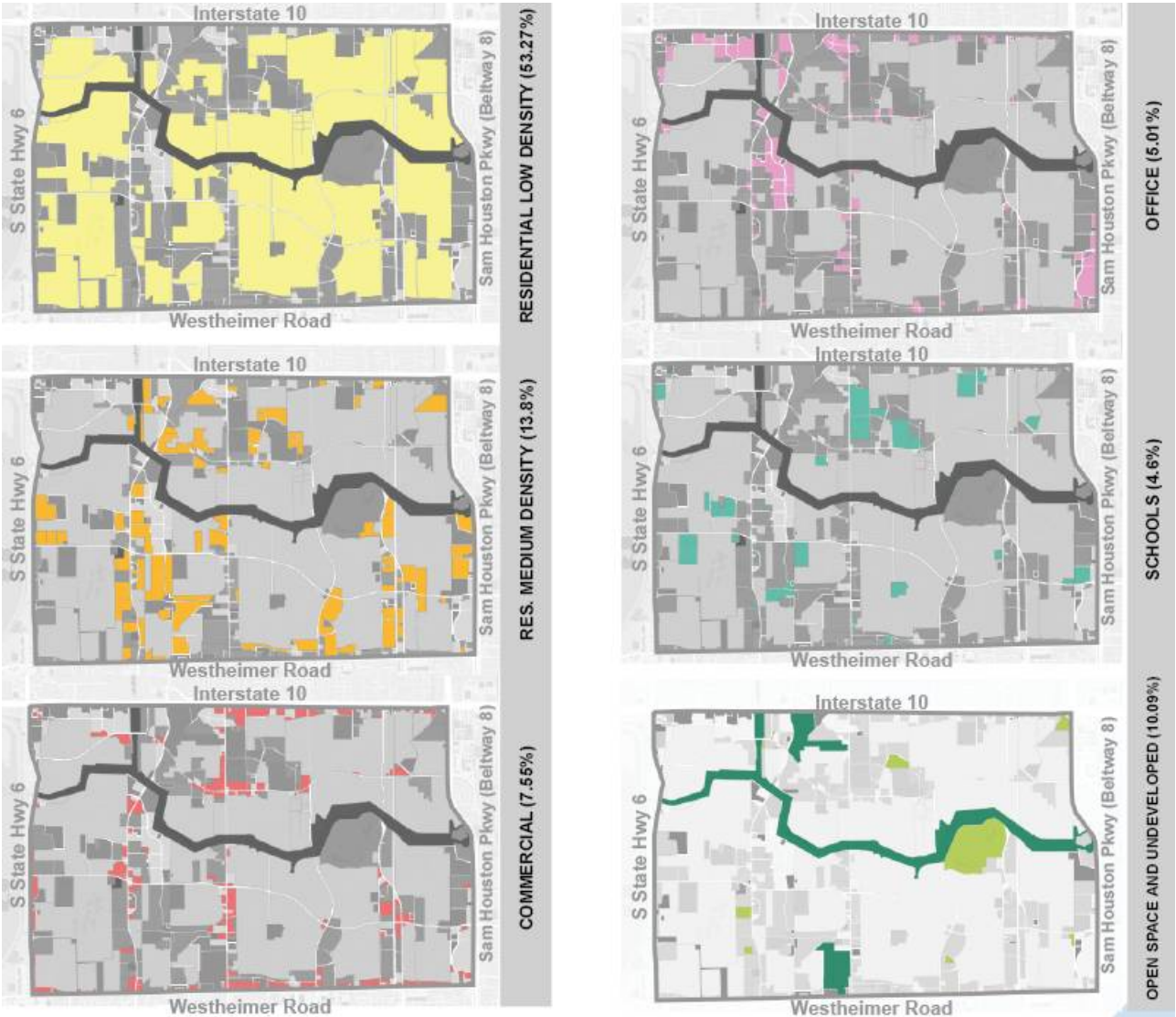
**Figure 5.** Current land use types and percentages within the pilot study area.

High urbanization and concrete coverage, and extreme occupation of the 100-year and 500-year floodplains are characteristics of this area, which had one of the highest estimated number of affected units in the region during Hurricane Harvey - approximately 19,843 - according to FEMA data from December 2017, and one of the highest number of applications for individual assistance[15].

The combined 1% (100-year) and 0.2% (500-year) floodplains (Figure 6) cover an estimated area of 2,420 acres within the study area, approximately 22 percent. Harris County Flood Control District (HCFCD) estimates there are 184,546 structures inside the 1% (100-year) FEMA floodplain and 230,838 structures inside the 0.2% (500-year) FEMA floodplain within Harris County's 22 watersheds, as of June 2018. [16]

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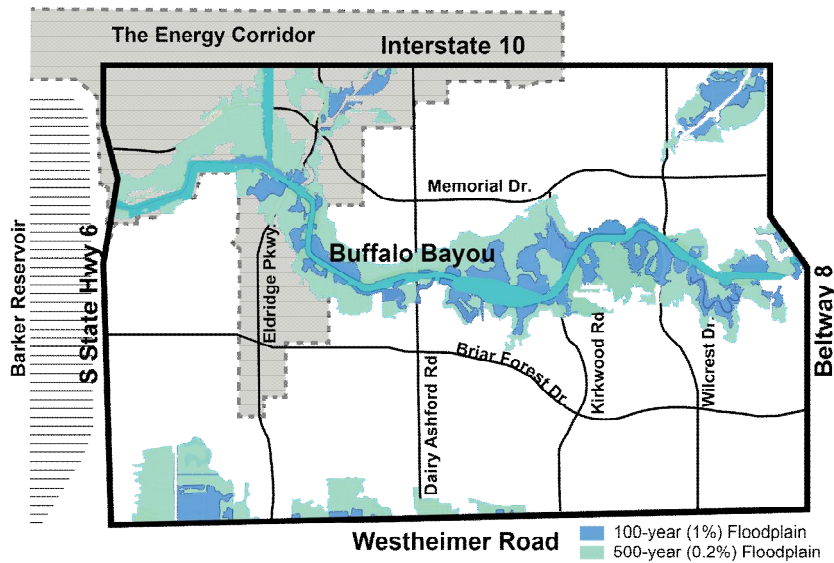
154 **Figure 6.** Floodplain coverage in the pilot study area.

**Phase 2. Identifying Priority Areas within the pilot**

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156 Based upon FEMA data post-Harvey [17], the pilot study area was then subdivided into three
157 categories A, B and C. These categories represent the number of structures damaged during the
158 hurricane for each of the 57 Census Block Groups (CBG), and will assist on identifying particularly
159 sensitive areas that should be prioritized. Category A includes areas with a number of damaged
160 structures between 500 and 1600 per CBG. Category B, between 300 and 499 per CBG. Category C,
161 between 1 and 299 per CBG. Table 1 and Figure 7 show the results of this method.

162 **Table 1.** Number of damaged structures/acre for Priority Areas categories A, B and C.

| Priority Areas | | | | |
|---|---|---|---|---|
| **Category** | **# of Census Block Groups** | **Total # of damaged structures** | **Total Land Area (acres)** | **# of damaged structures/acre** |
| **A** (500 to 1600 per CBG) | 14 | 9,255 | 3,270 | 2.83 |
| **B** (300 to 499 per CBG) | 14 | 5,735 | 2,867 | 2.00 |
| **C** (1 to 299 per CBG) | 29 | 4,853 | 4,672 | 1.03 |

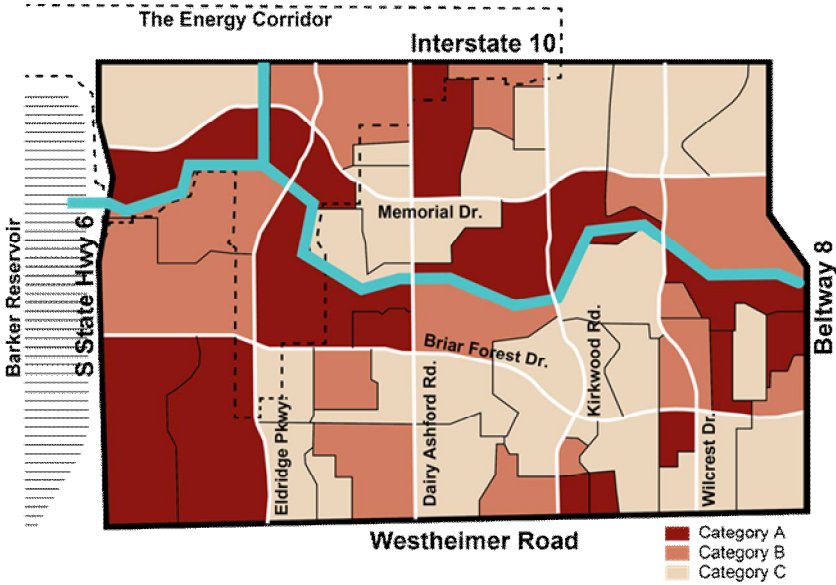



**Figure 7.** Priority areas in the pilot study area.

Category A areas shown on Figure 7 had the highest number of damaged structures per acre and became the focal point of the pilot study area. Most of these areas are located along the 6.4 linear miles of Buffalo Bayou between State Highway 6 and Beltway 8, and the remaining areas flooded as result of an overwhelmed drainage network.

**Phase 3. Exploring flood volume reduction options**

Low Impact Development (LID), Sponge Cities, Eco-Boulevards, Water Squares and Green Alleys were concepts taken into consideration.

LID is a comprehensive land planning and engineering design approach with the goal of maintaining the pre-development hydrologic regime in a watershed without solely using conventional development and detention basin techniques to satisfy drainage and flood mitigation requirements. Acceptable LID practices include bioretention, rainwater harvesting, green roofs, permeable pavement and underground stormwater storage, among others [18].

The Sponge City concept was launched by the Chinese Central Government in selected pilot cities across China in 2014, primarily as a response to increasing flood impacts. The Sponge City approach aims to enhance infiltration, evapotranspiration, and capture and reuse of stormwater in the urban environment. Some of the anticipated benefits of this concept are the reduction of economic losses due to flooding and enhancement of the livability of cities [19]

The Eco-Boulevard concept is presented in various forms. One architecture firm in Chicago, Urban Lab, has partnered with the City of Chicago to cultivate the Eco-Boulevard project and transform streets into eco-boulevards that could treat the city's wastewater and stormwater naturally. Their approach is to transform existing roadways, sidewalks and parks (the public-way) into a holistic, distributed, passive bio-system for recycling Chicago's water and return all treated water to the Great Lakes, closing Chicago's water loop [20]. Since 2006, more than one hundred Green Alleys and Eco-Boulevards have been built in Chicago as stretches of permeable pavement and bioswales that allow storm waters to filter through and drain into the ground below, where microbes remove bacteria and pollutants before the water is allowed to run into nearby Lake Michigan. "The Green Alleys create porosity and permeability so that the water can move in the ways that it moves in the hydrological cycle", according to Jay Homack, a senior landscape architect who designed most of the infrastructure [21].

Water Squares combine water storage with the improvement of the quality of urban public space. They are generally used in inner-city areas with little room for water buffers and where high groundwater levels make infiltration difficult. Water Squares can be understood as a dual-strategy

198 that makes the money invested in water storage facilities visible and enjoyable. They also generate
199 opportunities to create environmental quality and identity to central spaces in neighborhoods. Most
200 of the time a water square will be dry and used as a recreational space [22,23].

202 **Figure 8. Water Square in Benthemplein, Rotterdam, NL.**
203

**Figure 9. Green Alley. San Francisco Public Utilities Commission.**

204 **Phase 4. Calculating detention volume for a 1% probability, 24-hour storm**

205 The Watershed Modeling method involves use of the HCFCD hydrologic methodology
206 developed to identify flood damage reduction and mitigation projects for drainage areas greater
207 than 640 acres in Harris County [24]. Depths of direct runoff for the 24-hour, 1% probability rainfall
208 event selected for this model are provided in the HCFCD Policy Criteria and Procedure Manual
209 (PCPM) for each rainfall region [25]. Buffalo Bayou is classified as Region 2 and estimated direct
210 runoff values for three impervious conditions are shown on Table 2.

211 **Table 2.** Direct runoff values for Buffalo Bayou watershed according to HCFCD-PCPM [27].

| Watershed Name | Rainfall Event Probability | Total Rainfall (inches) | Direct Runoff (inches) | | |
|---|---|---|---|---|---|
| | | | 0% impervious | 40% impervious | 85% impervious |
| Buffalo Bayou | 24-hour, 1% | 13.2 | 11.1 | 12.0 | 12.9 |

212 The approximate acreage of impervious surface within the pilot study area was calculated by
213 multiplying the Percent Impervious Cover Per Land Use values [26] from the HCFCD Policy
214 Criteria and Procedure Manual by the total acreage of each land use type obtained in Geoplanner for
215 ArcGIS (Table 3).

216 **Table 3.** Total impervious area per land use type.

| Land Use Type | Undev. | School | Office | Public/ Institut. | Industrial | Church | Commercial | Resid. Low Density | Resid. Medium Density | Resid. High Density | Utilities | Open Space Parks | Open Space Conserv. | Roads | Total (acres) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % Impervious Cover | 0 | 40 | 60 | 60 | 60 | 40 | 85 | 20 | 65 | 85 | 60 | 15 | 15 | 90 | |
| Total Area (acres) | ±301 | ±465 | ±506 | ±45 | ±37 | ±103 | ±763 | ±5,380 | ±1,394 | ±36 | ±52 | ±278 | ±741 | ±708 | ±10,809 |
| Impervious Area (acres) | 0 | ±186 | ±304 | ±27 | ±22 | ±41 | ±649 | ±1,076 | ±906 | ±31 | ±31 | ±42 | ±111 | ±637 | ±4,063 |

219 **Summary of acquired data:**

220 Total rainfall = 13.2 inches

221 Duration of storm = 24 hours

222 Probability = 1%

223 Contributing area in watershed = 10,809 acres

224 Total estimated impervious surface area = 4,063 acres

225   Runoff Depth = 12.9 inches = 1.075 feet*

226   *Although generalized relationship between percent land development and percent impervious cover differs
227   between various land uses, in the best interest of this study all land uses within the pilot area were considered
228   high-density or 85% impervious, with a runoff depth of 12.9 inches on a 100-year, 24-hour storm event. This
229   classification was deemed appropriate due to the predicted growth in the region for the next decades, to the
230   hydrologic soil classification throughout the area (Group D - poorly drained), and to the evident need for a
231   drainage system that can endure storms of greater magnitude.

232

233   Based on this information, the total detention volume needed for a 100-year, 24-hour storm
234   event in the study area should be 88,492 cubic feet (VT= [43,560 x (0.50 x impervious area)]) or 4,368
235   acre-feet (impervious area 4,063 acres x direct runoff 1.075 feet).

236

237   **Phase 5. Detecting potential sites for the implementation of flood mitigation strategies**

238   In order to have quantitative evidence of the pilot area's capability to accommodate the elected
239   strategies, the Land Use map generated in Geoplanner for ArcGIS software - with land use data
240   from the City of Houston GIS portal (Figure 4) - was examined, and vacant and undeveloped areas
241   were outlined for each parcel of land within the pilot area. The objective was to obtain a final
242   acreage of potential stormwater detention/storage sites, publicly or privately owned, per land use
243   type.

244   **Table 4.** Total acreage of potential stormwater detention and storage per land use type.

| POTENTIAL STORMWATER DETENTION AREAS | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Land Use Type | Undeveloped | School | Office | Public | Industrial | Church | Commercial | Residential | Total |
| Vacant or Undeveloped (acres) | ±19 | ±63 | ±20 | ±331 | ±10 | ±8 | ±5 | ±28 | ±484 |

245

246   **3. Results**

247   Assuming the area's existing drainage system is adequate and provides the detention volume
248   required for a 100-year, 24-hour storm event - as specified in the HCFCD-PCPM - this study aimed
249   to identify opportunities to reduce riverine flooding along Buffalo Bayou as well as to identify
250   potential locations for mitigation of secondary local drainage, during unforeseen storm events.
251   Embedded in this purpose is the development of urban design concepts that propose to enhance
252   quality of life of area residents while reducing flood threat.

253   *3.1. Proposed flood mitigation strategies*

254   In April, 2018 FEMA amended the longstanding 100-year floodplain standard for new projects
255   such that most new buildings will now have to be two feet freeboard. Freeboard is a factor usually
256   expressed in feet above a flood level for purposes of building above a floodplain. Today, building
257   codes in many jurisdictions require construction to be 1-foot freeboard. The City Public Works
258   Department produced an analysis showing that the projected water level in a 500-year floodplain
259   plus a 2-feet elevation would have spared 84% of homes in city floodplains during Hurricane
260   Harvey [27]. Considering these results, the stormwater detention volume was recalculated to reflect
261   a runoff depth of 24 inches.

262   **Summary of the adjusted data:**

263   Total rainfall = 24.5 inches

264   Duration of storm = 24 hours

265   Probability = 1%

266   Contributing area in watershed = 10,809 acres

267   Total estimated impervious surface area = 4,063 acres

268   Runoff depth = 24 inches = 2 feet

269   $V_T$= (impervious area= 4,063 acres x direct runoff= 2 feet) = 8,126 acre-feet

270   Subtracting 4,638 acre-feet of provided detention volume from the 8,126 acre-feet new required

271   detention volume, the goal is to provide the remaining 3,758 acre-feet of stormwater detention

272   possibilities.

273   3.1.1. Along Buffalo Bayou

274   Allocation of stormwater storage cisterns in the 279 acres of public land along the Buffalo

275   Bayou. These are underground units to be positioned along Buffalo Bayou at intervals to be

276   determined contingent to technical feasibility. Each unit is to be connect to the bayou through an

277   inlet-outlet pipe at an angle to be determined. During a storm event, if the Bayou reaches a critical

278   level, the water pressure will cause the connection to the unit to open, redirecting part of the flow of

279   water from the bayou into that unit. Once the unit is full, the water pressure inside the unit will

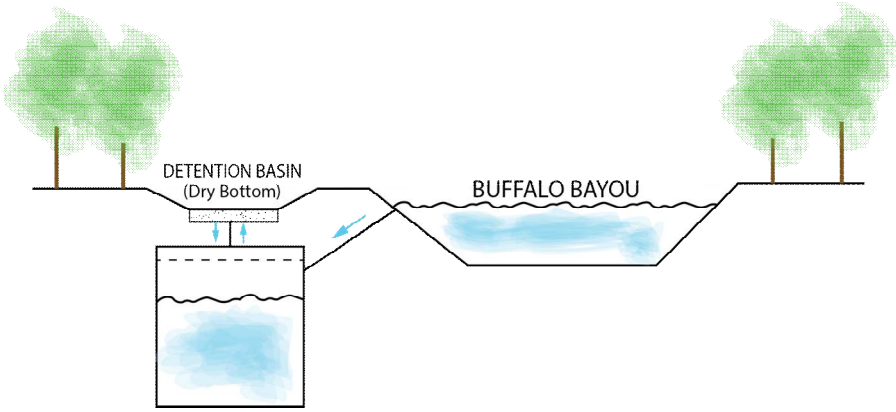
280   cause the connection to the bayou to shut. These units will be also collecting rain from detention

281   basins located above them, and a layer of engineered soil between the basin and the unit will

282   promote the filtration of the water before it enters the unit. Eighteen cisterns along Buffalo Bayou's

283   6.4 linear miles between State Highway 6 and Beltway 8 (Figure 11), each with a 51.65 acre-feet

284   capacity (2,250,000f³), would provide 930 acre-feet of stormwater detention volume in the pilot

285   study area.

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287   **Figure 10.** Schematic of the proposed underground stormwater storage unit.

288

PRIORITY AREAS

100-YEAR FEMA FLOODPLAIN

500-YEAR FEMA FLOODPLAIN

● POTENTIAL LOCATION FOR UNDERGROUND STORMWATER STORAGE AND DETENTION BASINS

----- MAIN ACCESS ROADS

········ BOUNDARY OF STUDY AREA

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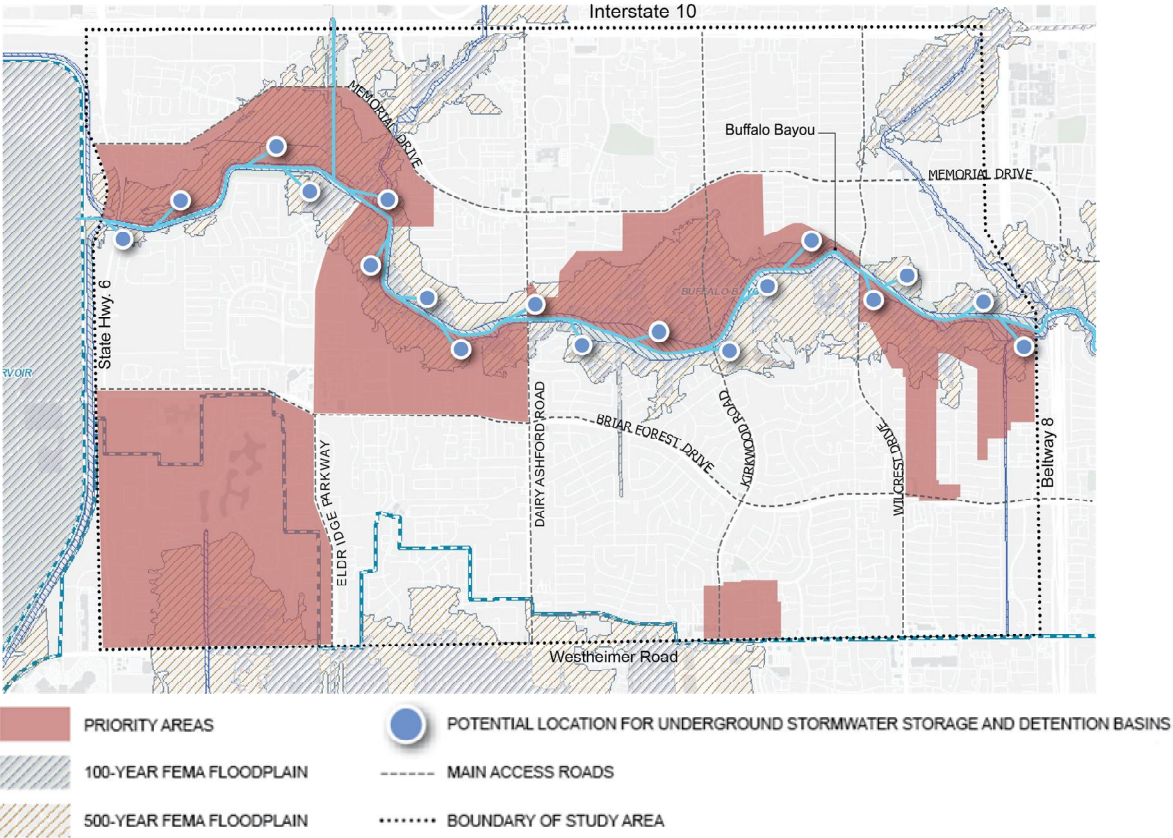
290    **Figure 11.** Potential sites for underground stormwater storage units along Buffalo Bayou.

291    3.1.2. Beyond Buffalo Bayou

292    Approximately 205 acres* of private and public vacant land were identified with Geoplanner
293    for ArcGIS as potential stormwater detention development areas (Table 4). Those sites consist of
294    vacant lots and segments of undeveloped land from school, commercial, office, church, industrial
295    and residential uses. Many of those areas have the potential to being converted into flood mitigation
296    sites through the implementation of localized storm drainage enhancements, such as the use of LID
297    methods and, when feasible, the incorporation of underground stormwater storage units.
298    Contingent upon the neighboring land uses, community enhancements like parks, splash pads,
299    sport courts or water squares/circles could also be incorporated. An initial approach identified fifty
300    possible sites where underground stormwater storage units could be implemented (Figure 13). That
301    number of units would provide 2,582 acre-feet of detention volume.

302    *205 acres = 484 acres total potential stormwater retention sites minus the 279 acres of public land along
303    *Buffalo Bayou.*

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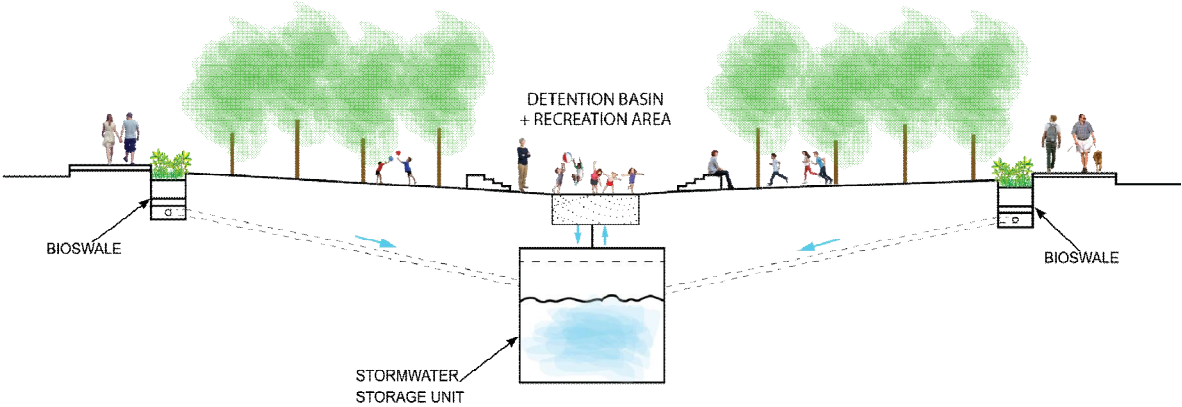
305        **Figure 12.** Schematic of stormwater storage unit under proposed recreation area.

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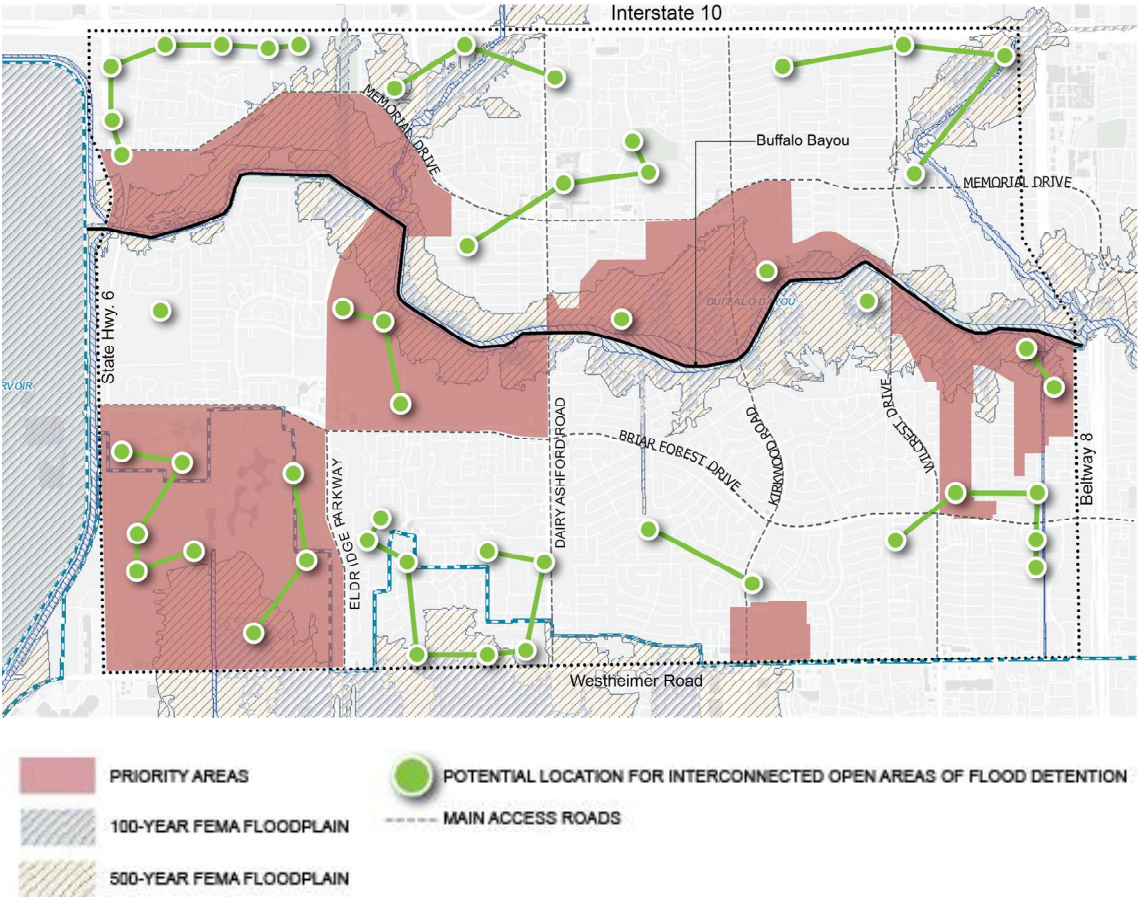
**Figure 13.** Vacant/undeveloped sites for potential stormwater detention and storage beyond Buffalo
Bayou.

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310    3.1.3. Underground Stormwater Detention Vaults

311        Approximately 116 acres of parking lot area were identified with Geoplanner for ArcGIS as
312    potentially suitable sites for the construction of underground storage vaults within the study area.
313    Subsurface stormwater storage provides minimal stormwater quality benefit, but can be
314    successfully used for reduction of stormwater runoff flow. It is also a good option for high density or
315    urban areas with limited permeable area. From the initial 3,758 acre-feet of detention volume
316    needed, 3,512 acre-feet can potentially be reached through the implementation of underground
317    stormwater storage units along Buffalo Bayou and at the undeveloped sites shown on Figure 13. The
318    remaining 245 acre-feet of detention volume can clearly be obtained with the construction of these
319    underground storage vaults throughout the area.

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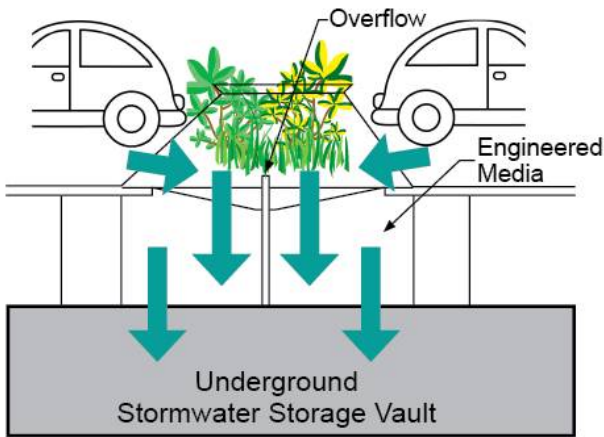
321             **Figure 14.** Bioswales carry parking lot stormwater runoff to underground storage vault.

322     3.1.4. Eco-Boulevards and Green Alleys

323     Figure 15 represents the conceptual design of a Green Alley connecting Nottingham
324     Elementary School to Buffalo Bayou and Dairy Ashford. The school is encroached on a highly
325     populated area and surrounded by Nottingham Forest - an eight-hundred home subdivision - two
326     apartment complexes, a church, retail and restaurants. The total distance from the school to Buffalo
327     Bayou is 0.56 miles of curvy vegetated trails of permeable pavers with bioswales and bioretention
328     cells alongside them. These LID features are connected to one or more underground stormwater
329     storage units. One of these units is installed underneath the 34,064sf lot/vacant restaurant for sale at
330     the corner of Memorial Drive and Nottingham Oaks Trail, converted into a splash park/water circle
331     over that unit. In addition to improving stormwater drainage in areas very susceptible to flooding,
332     eco-boulevards can provide multiple ecological and social benefits, promoting connectivity and a
333     healthy quality of life.

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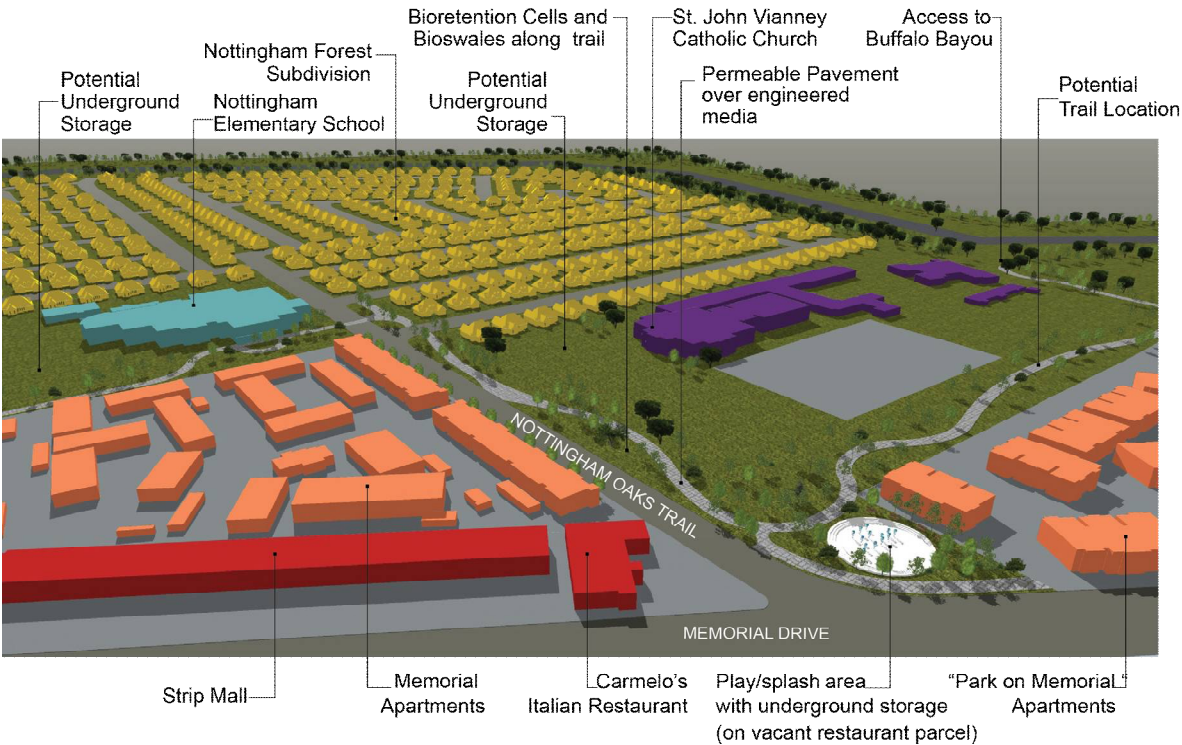
335             **Figure 15.** 3D rendering of conceptual green alley produced with Esri City Engine.

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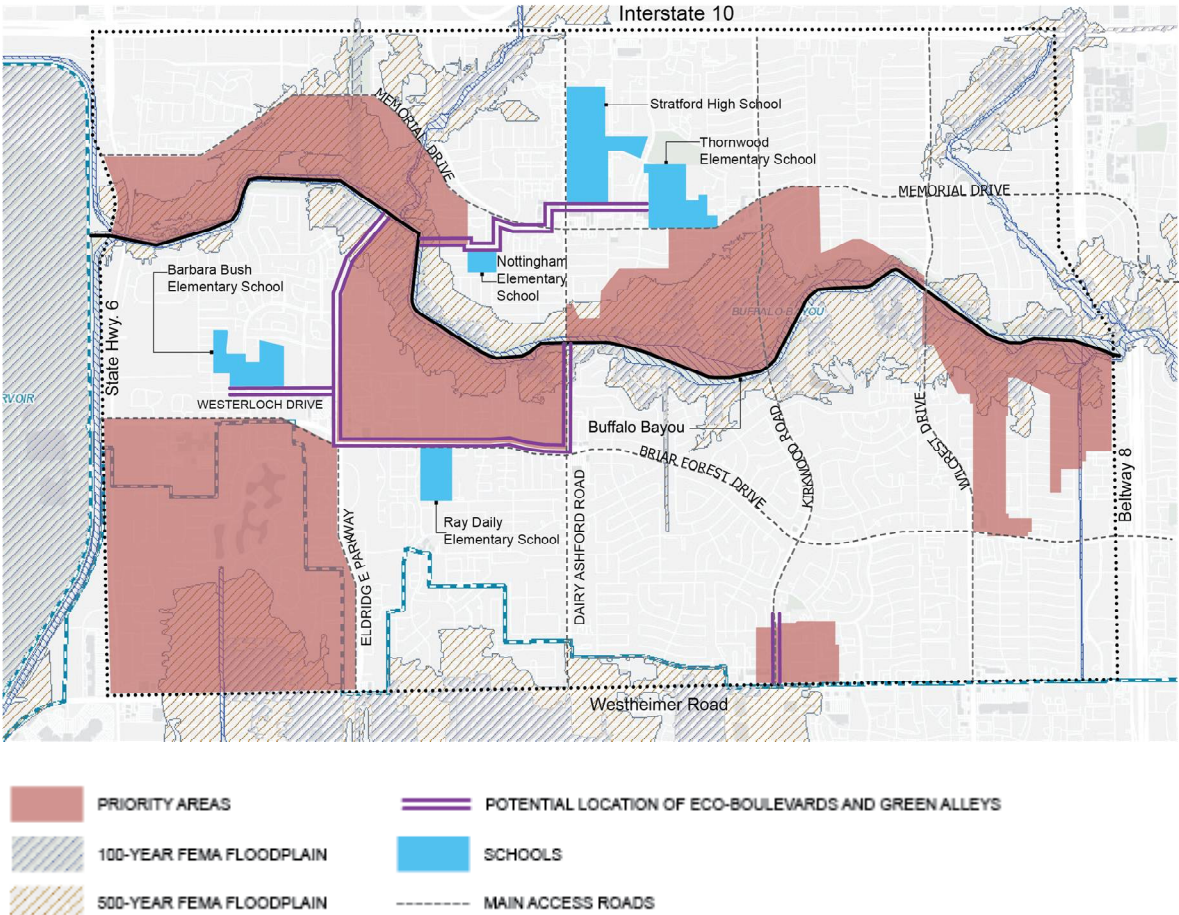

338          **Figure 16.** Potential locations of Eco-Boulevards and Green Alleys.

339     **4. Discussion**

340          Several projects have been under discussion to determine how to protect Houston from
341     flooding. A third reservoir upstream from the Addicks and Barker Reservoirs in northwest Harris
342     County is one of them. A Coastal Spine Storm Surge Protection System creating a sixty-mile coastal
343     barrier between hurricane storm surge and Galveston Bay is another. On August 14, 2018, Harris
344     County Commissioners Court approved a list of 237 flood risk-reduction projects that would meet
345     the goal of the 2018 bond election. On August 25th, Harris County voters approved two and a half
346     billion in bonds to finance flood damage reduction projects in Harris County, including channel
347     modifications, regional stormwater detention basins, major repairs to flood-damaged drainage
348     structure, voluntary buyouts of flood-prone properties, wetland mitigation and property acquisition
349     for preserving natural floodplains, amongst others. High in the priority list are construction-ready
350     projects with funding partners such as USACE and FEMA. From the 237 projects, 22 are designed to
351     the improvement of the Addicks and Barker Reservoirs, and will be evaluating the reservoirs'
352     effectiveness and operation, de-silting channels upstream to restore channel conveyance capacity,
353     performing right-of-way acquisitions, constructing wetland mitigation banks and rehabilitating
354     channels inside the reservoirs [28]. Also as part of the 2018 flood bond program, HCFCD is set to
355     receive a federal grant to study the feasibility of constructing deep underground tunnels to move
356     stormwater to the Houston Ship Channel without overburdening the area's bayous. Engineers
357     envision a system in which tunnels at least twenty feet wide and one hundred and fifty feet deep use
358     gravity to move water from upstream bayous to the Ship Channel, in some cases a distance of thirty
359     miles. The region's flatness, soft soil and high water table present a significant obstacle, but similar
360     low-lying cities such as Washington D.C. have been able to use this method of flood control [29].
361          Current HCFCD proposed bond projects that include the pilot study area consist of drainage
362     network repairs, construction of detention basins along Buffalo Bayou, and studies to be performed

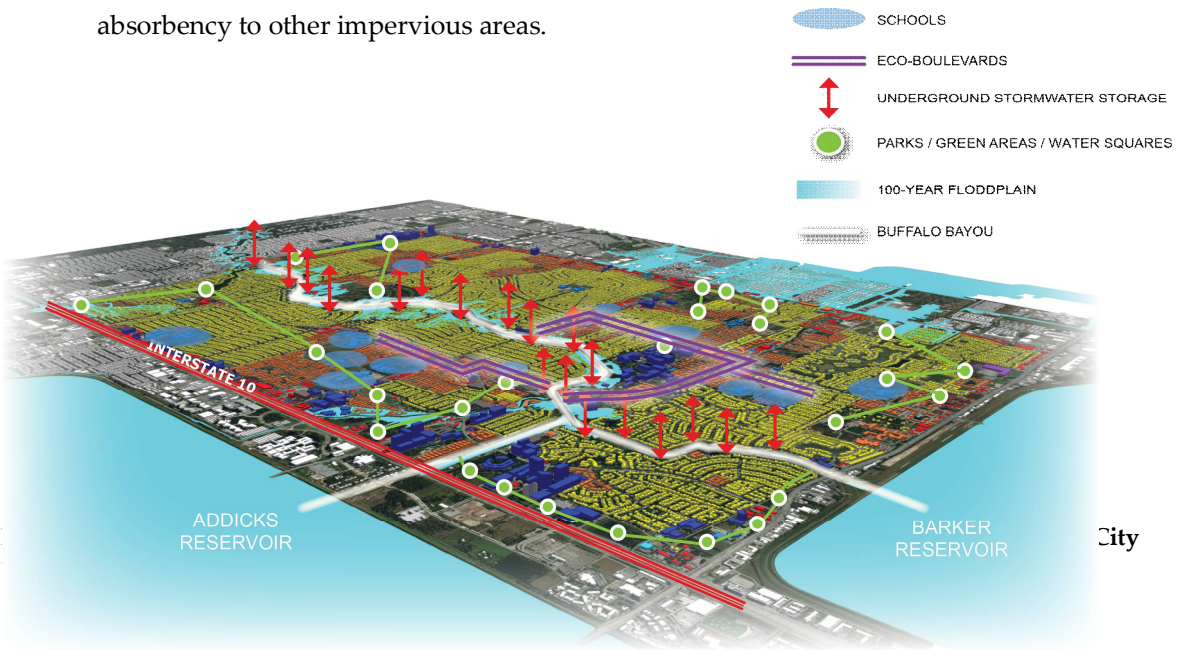
363  by USACE, such as the *C-40 Study of Addicks and Barker Reservoirs* and *The Buffalo Bayou and*
364  *Tributaries Resilience Study*, to address flooding downstream and upstream of the reservoirs.

365      The present research was intended to examine potential ways to reach efficient flood control
366  while indorsing sustainability. For instance, the reclamation of stormwater – a natural asset too
367  important to be discarded - with the use of underground storage. The sustainabilization of urban
368  areas via integration of LID methods. And the enhancement of community areas to promote a
369  healthier lifestyle, with the implementation of green alleys, water squares and eco-boulevards.

370  **5. Conclusions**

371  - The methodology applied in this study has proved to expedite the research process.
372    Outlining priority areas based on the number of structures damaged by Hurricane Harvey
373    helped detect sources of flooding that could be irradiating the problem to surrounding areas
374    and needed special attention.

375  - Some walkability challenges found in the study area included poor or deteriorated
376    sidewalks, paths that dead-end or connect to nowhere, and lack of safer street design
377    standards. Developing attractive, comfortable and safe built environments - in which
378    people could engage in outdoor activities without having to drive to the destination - and
379    incorporating to that concept flood mitigation strategies, is a possibility substantiated in
380    this study. Approximately 5.28 miles of potential Green Alleys and Eco-Boulevards were
381    identified in the pilot study area, with the capability of connecting neighborhoods and
382    schools to infrastructure services, parks and to Buffalo Bayou trails. In addition to the social
383    and economic benefits discussed, the use of LID practices such as bioswales and permeable
384    pavements in the concept would substantially improve the areas' resilience to flooding.

385  - 3,758 acre-feet (163,698,480 cubic feet) of stormwater detention volume were deemed to be
386    required in order to provide flood protection to the 10,809-acre study area in a model
387    24-hour, 1% probability storm with a total rainfall amount of 24.5 inches. The proposed
388    underground storage units can potentially provide the total detention volume and be
389    incorporated to most priority areas. The underground storage vaults in parking lots and the
390    LID tools integrated to green alleys and eco-boulevards would work in parallel to ensure
391    absorbency to other impervious areas.

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