Houston Solutions Lab 2017 Project Report

SMALL-SCALE APPLICATIONS OF DISTRIBUTED HYDROLOGIC MODEL VFLO® TO CHARACTERIZE IMPACTS FROM MITIGATION PROJECTS

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EXECUTIVE SUMMARY

This project characterizes the hydrodynamics of local neighborhoods and evaluates the effectiveness and impacts of various mitigation measures by using a distributed hydrologic model. With recommendations from the City of Houston (COH), three flood-prone residential neighborhoods were selected for analysis: Sunnyside, Regency Area, and Briar Patch. For each study area, surface runoff based on multiple design storms (i.e., 2-yr, 5-yr, 10-yr, and 100-yr) were simulated to better understand existing flow characteristics. Based on these results, various mitigation options were considered and their impacts analyzed.

I. INTRODUCTION

The Greater Houston Region has always been prone to flooding due to intense rainfall, flat topography, and predominantly clay soils. Rapid urbanization in the region, however, has exacerbated Houston's flood vulnerability, especially in recent years. This is especially true in densely populated watersheds such as Brays Bayou and Buffalo Bayou. While there are existing flood mitigation projects in these watersheds, these, along with many prevalently used hydrologic models focus almost exclusively on riverine flooding. In fact, FEMA's 100-yr floodplains are delineated by using one such model. As various studies have shown, these floodplain maps often underestimate the actual flood risk in a watershed due to not adequately accounting for other drivers of flood risk such as localized ponding and drainage issues. To better understand the flood risk at the site level, a hydrologic model that is capable of adequately representing the spatial variability within a relatively small area (e.g., neighborhood scale) would be necessary.

This project utilizes a distributed hydrologic model to assess street-level flood vulnerability in three residential areas in Houston, which were then used in the consideration of various mitigation options. The following sections describe the overall methodology and subsequently discuss each project area in detail.

II. METHODS: DISTRIBUTED HYDROLOGIC MODEL - VFLO®

The distributed hydrologic model, Vflo®, was developed by Vieux and Associates, Inc. to simulate the hydrodynamics of a watershed by using a finite element approach. Vflo® uses a series of inter-connected network that represent both overland and channel flow in a watershed. The Vflo® domain consists of a grid system that contains overland and channel cells in which each cell is connected by a flow direction arrow. There are eight possible inflow directions for each cell that can be calculated from elevation data. Cell properties, such as elevation, land cover, and soils data, are processed spatially in GIS and imported into Vflo® (see Figure 1). Using this information, Vflo® calculates the conservation of mass and momentum equations to simulate the rainfall-

runoff process of each cell. Overland routing is handled using the kinematic wave approach, channel routing via the Modified Puls method, and infiltration with the Green and Ampt method.

For this project, separate Vflo® models were developed for each study area. The terrain data used for all study areas was the 2008 LIDAR (Light Detection and Ranging) from HGAC (Houston-Galveston Area Council), and the soils data from NRCS (Natural Resources Conservation Service). To represent existing conditions, the 2011 LULC (land use / land cover) and 2011 impervious cover datasets from NLCD (National Land Cover Database) were used. To better understand flow characteristics of each study area, multiple 24-hr duration design storms ranging from approx. 4 inches (2-yr) to 13 inches (100-yr) were simulated. The results of these analyses were used as a basis for the consideration of various mitigation options in each project area.

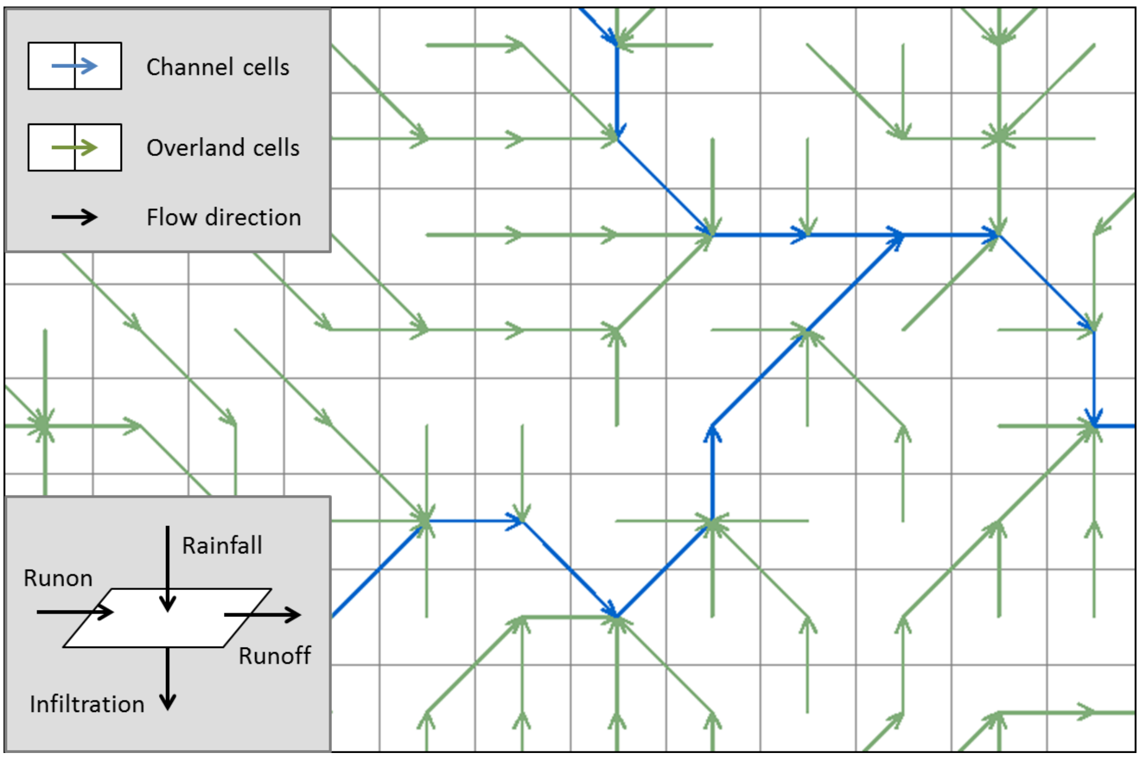

Figure 1: Vflo® domain overview

III. SITE 1: SUNNYSIDE

Site Overview and Model Setup

The Sunnyside project site is located south of I-610 S and east of SH-288 in Sims Bayou watershed (Figure 2). The site is mostly residential, covering an area of 92 acres. Bordering west of the project site is a park (Sunnyside Park) and a landfill. Combined, the park and landfill constitute approximately 285 acres.

A Vflo® model with 30-ft cell resolution was developed for this site. The domain covers ~407 acres, which is much larger than the 92 acres of the actual site, in order to identify and capture the contributing drainage areas. Based on the analysis of drainage areas at the project site, three watch points were identified (Figure 3): Northeast (Bellfort St.), East (Alvin St.), and Southeast (Reed Rd).

Figure 2: Sunnyside project Location

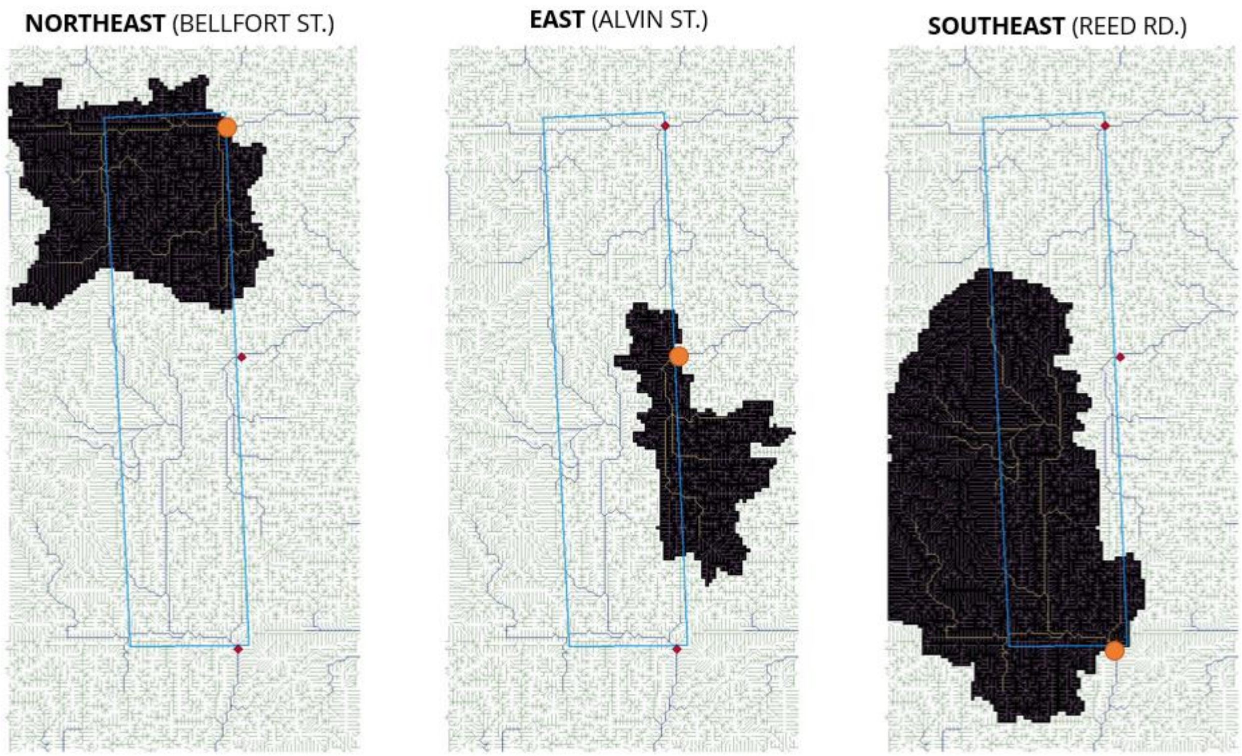

Figure 3: Sunnyside watch points and drainage areas

Hydrologic Analysis

Drainage area analysis reveals that most of the site, as well as a portion of the landfill drain toward Reed Rd. and Bellfort St. Meanwhile, only a small portion of local site runoff drains towards Alvin St. Furthermore, elevation map shows that roads / streets have higher elevations compared to the surrounding areas; therefore, runoff is mostly contained and conveyed by the roadside ditches and culverts. Figure 4 shows the simulated surface runoffs at each watch point under various storms. Based on these results, the existing culverts (i.e., 18 in. round pipes) are found to be insufficient in containing local site runoff from a 2-yr storm. Any additional runoff (e.g., from the landfill) would have exacerbated this issue.

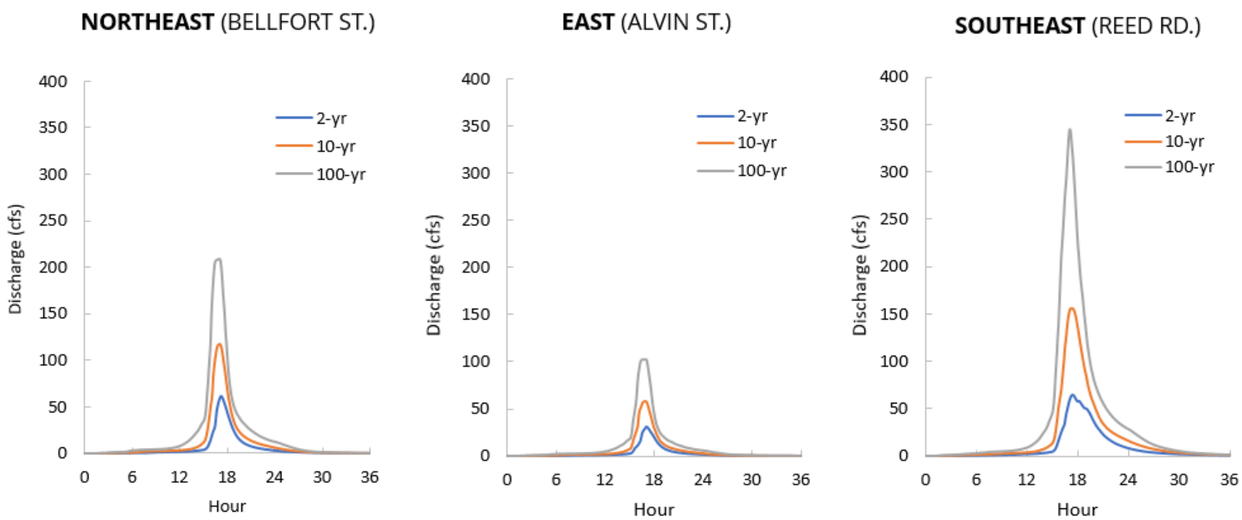

Figure 4: Vflo® modeled results

Flood Mitigation Analysis

After performing the above hydrologic analysis, several mitigation options were considered. Eventually, two mitigation options (Figure 5) were selected and evaluated:

1. Option A: Divert or detain runoff portion from the landfill + park and add / replace existing culverts to handle local site runoff
2. Option B: Replace existing culverts to contain runoff from both landfill and site
   - B1: 25% landfill + site = 71.25 ac + 95 ac = 166.25 ac
   - B2: 50% landfill + site = 142.5 ac + 95 ac = 237.5 ac

The mitigation scenarios assumed 6 total discharge points (outlets) for the entire project site, with each outlet having one culvert. Pipe / culvert calculations were performed using the Rational Method and Manning's equations, with the goal of complying with the 2017 COH drainage criteria.

Figure 5: Schematics of mitigation options

Option A: Divert or detain runoff portion from the landfill + park and add / replace existing culverts to handle local site runoff

As shown in the table below, the calculated minimum pipe diameter required at each of the 6 outlets ranges from 3 ft to 4 ft to comply with COH's drainage criteria of having pipe velocities between 3-10 ft/s.

Parameter	2-yr	5-yr	10-yr	100-yr
Peak flow (cfs)	403	494	556	747
Min. culvert diameter (ft)	3.0	3.5	3.5	4.0
Pipe velocity (ft/s)	9.5	8.6	9.6	9.9

Table 1: Option A pipe calculations

Table 2 shows the calculated detention storage needed to accommodate landfill runoff. Low and high estimates were provided based on the percentage of landfill area designed to be captured by the detention basin (i.e., low estimate: 25% of landfill area and high estimate: 50% of landfill area).

Parameter	2-yr	5-yr	10-yr	100-yr
Low estimate (ac-ft)	27	38	46	80
High estimate (ac-ft)	53	76	93	160

Table 2: Option A detention calculations

Option B: Replace existing culverts to contain runoff from both landfill and site

Tables 3a and 3b show the calculated culvert diameters required for Options B1 and B2 respectively.

Parameter	2-yr	5-yr	10-yr	100-yr
Peak flow (cfs)	705	864	973	1,308
Min. culvert diameter (ft)	4.0	4.5	5.0	5.5
Pipe velocity (ft/s)	9.4	9.1	8.3	9.2

Table 3a: Option B1 pipe calculations

Parameter	2-yr	5-yr	10-yr	100-yr
Peak flow (cfs)	1,007	1,234	1,389	1,868
Min. culvert diameter (ft)	5.0	5.5	5.5	6.5
Pipe velocity (ft/s)	8.6	8.7	9.8	9.4

Table 3b: Option B2 pipe calculations

Conclusions

Based on Vflo® results, there are substantial runoff contributions from the landfill into the Sunnyside residential area, especially the area between Alvin St. and Reed Rd. The minimum required culvert size to meet COH standards is 3 ft (for the 2-yr flow); however to mitigate flooding, larger culverts and (potentially) additional detention / storage are necessary. Three mitigation options were considered: Option A assumed that landfill runoff would be detained/ diverted and only considered local site runoff in culvert sizing calculations; Options B1 and B2 included estimates of landfill runoff in the culvert sizing calculations. In tandem with increases in culvert sizes, roadside ditches would also need to be modified proportionally to accommodate runoff.

IV. SITE 2: REGENCY AREA

Site Overview and Model Setup

The Regency project site is located within Brays Bayou Watershed in Southwest Houston near the intersection of Highway 59 and Westpark Tollway. The Regency Area, shown in Figure 6, has been highlighted as a hot spot for issues with pluvial flooding due to inadequate drainage by the City of Houston. The majority of the area is residential and commercial and is completely developed. Brays Bayou Watershed has a history of both fluvial and pluvial flooding issues due in part to the rapid westward urbanization upstream of the bayous and the cities aging infrastructure.

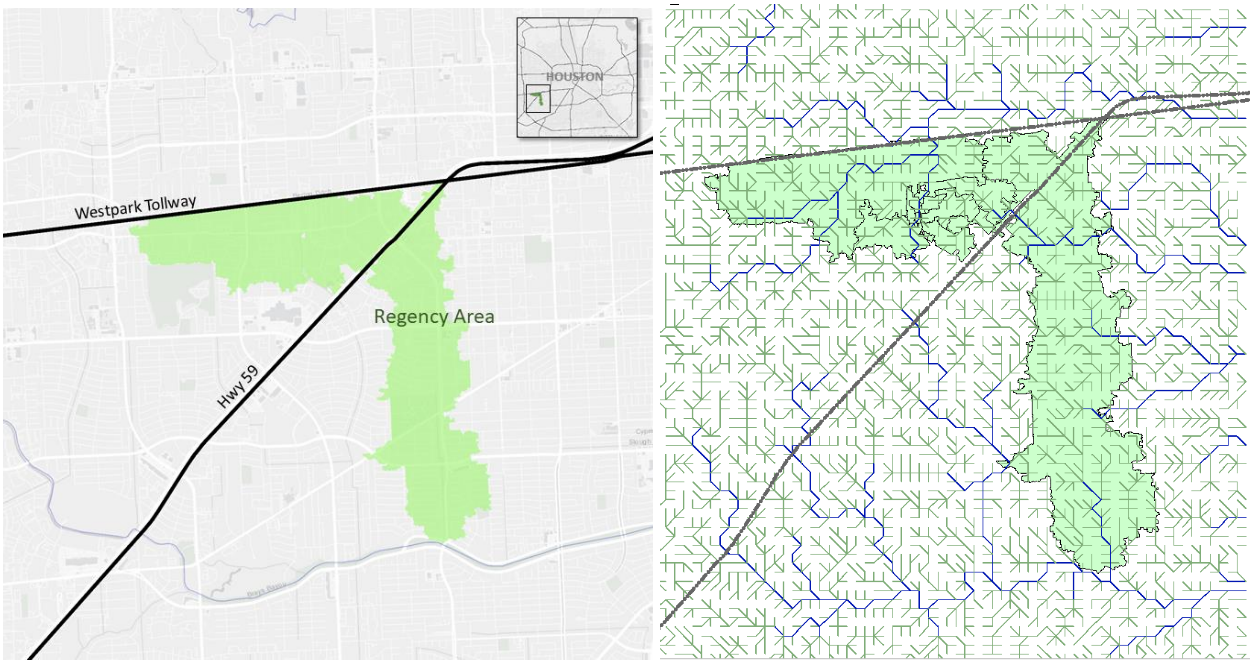

Figure 6: Regency Area project site (left) and Vflo® domain (right)

The Vflo® domain for this study area was developed by inputting available digital elevation model (DEM), land use, soil parameters, and imperviousness rasters. This domain shows flow direction and accumulation. From this information as well as the rainfall input, flow information at certain watch points can be obtained. For this project site, modeled overland flows from Vflo® were used to determine if the existing drainage system meets current design standards. Based on these results, modifications to the current storm-water drainage network and surrounding area were tested with the goal of increasing the capacity of the system to reduce the risk of pluvial flooding in local communities.

Hydrologic Analysis

To calculate the peak runoff for each of the major pipes in the drainage network for the Regency area, the rational method was used. First, the major pipes and culverts were identified, as seen in Figure 7. Then, contributing drainage areas were estimated in ArcGIS based on the subareas that overlapped with the existing drainage network. To calculate the peak flows for the 2-, 5-, 10-, and 100-year, the rational method was applied using these subareas and each of the respective rainfall intensities. The continuity equation was applied for each of the scenarios to determine the velocities in each of the existing pipes and compare them to the standard design capacities for storm-drainage in Houston.

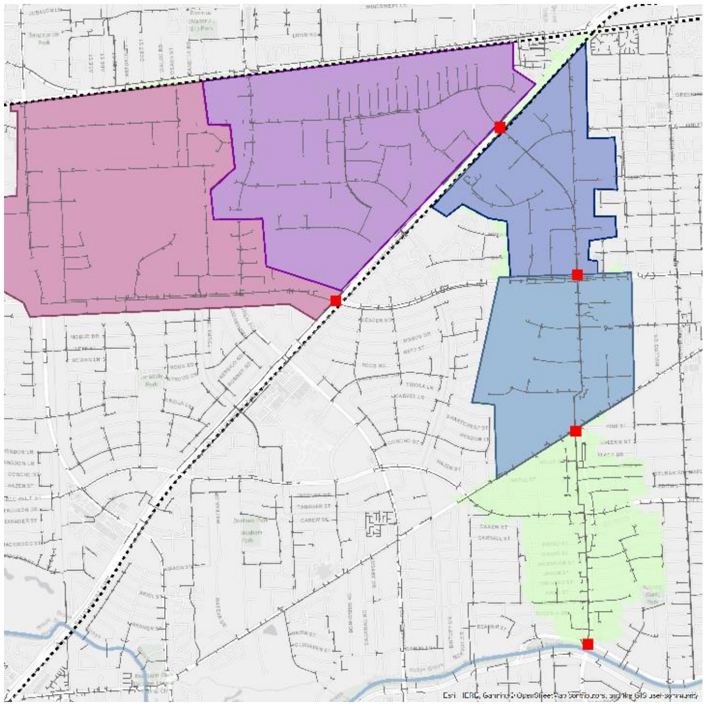

Figure 7: Major storm sewer pipes and contributing drainage areas

This exercise showed that the existing infrastructure in place was not sufficient to convey the water for over a 5-yr storm in the neighborhood. Furthermore, Vflo® also showed that the modeled surface runoff flow directions were somewhat different from storm drainage system's layout / configuration (see Figure 8).

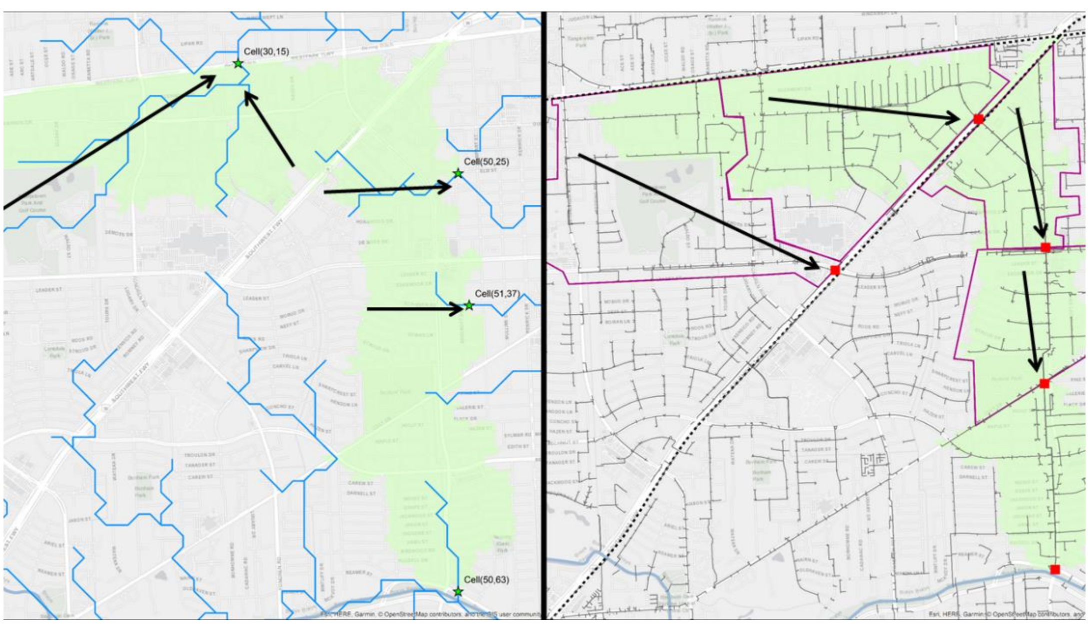

Figure 8: Modeled surface runoff flow direction / accumulation of Vflo® (left) vs City of Houston storm drainage network (right)

The significance of this difference in flow direction / accumulation would become evident when the storm sewer pipes are overwhelmed by a greater volume of water than their design capacities during severe storms, thereby inundating their surrounding areas.

Flood Mitigation Analysis

To alleviate the existing flooding problem in this area, a detention option coupled with pipe replacement was considered. Detention was applied in the Northern portion of the Regency area because it was deemed that it would be most effective. This option was also feasible due to the lack of development in this location because of its proximity to numerous power lines and the potential availability of incorporating an already existing green space for additional flood storage (Figure 9).

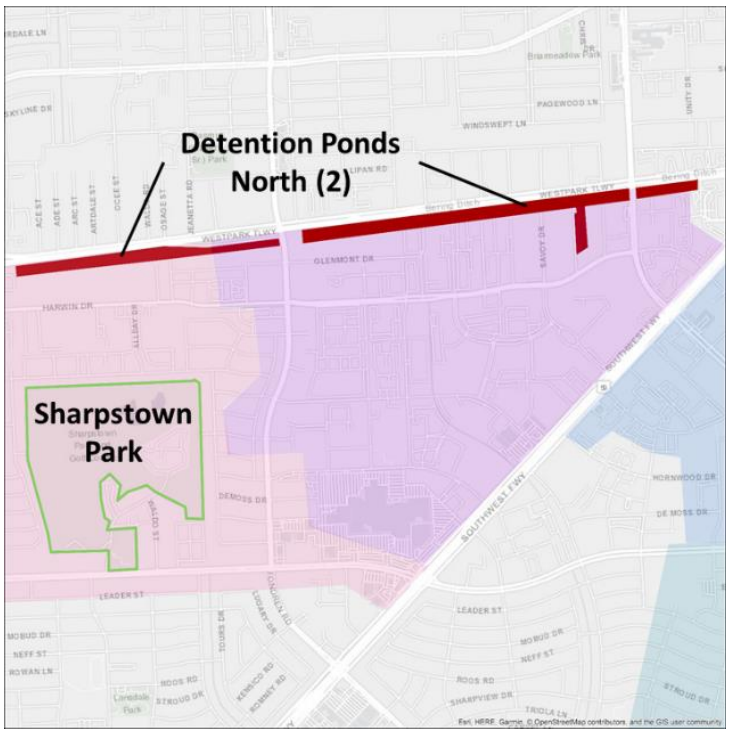

Figure 9: Location of proposed detention

The volumes for the detention ponds were estimated using a peak shaving method. This method is used when a pond is used to divert the peak flow of water above a certain flow of water that would not be able to be conveyed by the culverts and pipes alone. This additional water is stored in the detention ponds and released at a slower rate later to lower the peak flow of water. Peak shaving volumes for the ponds were recommended based on the peak flow of water for a given storm and were designed with 10-yr and 100-yr rainfall events in mind. The culverts in the Northeast and East sections were resized and additional culverts were added to accommodate the peak flow of water estimated for each of the design storms using the continuity equation and

based on design requirement of velocities ranging from 3 to 10 ft/s for stormwater drainage in Houston.

The resulting improvements suggested in the proposed mitigation option are shown in the following tables. Table 4 shows the suggested detention areas required for mitigation and Table 5 shows the resulting pipe replacements suggested and their corresponding 10- and 100-year results.

Detention Required	Area (Acres)	10-yr Volume Needed (ac-ft)	100-yr Volume Needed (ac-ft)	10-yr Depth (ft)	100-yr Depth (ft)
Sharpstown Park (N1)	178.4	2013.5	2792.5	11.3	15.7
Ponds 2 (N2)	55.4	667.6	1262.1	12.0	22.8

Table 4: Suggested detention areas and required capacities

Culvert Name	Current Pipe Diameter (ft)	10-year Peakflow (cfs)	100-yr Peakflow (cfs)	Proposed Pipe Diameter (ft)	Velocity Check (ft/s)
N1	2.5	49.00	49	2.5	9.89
N2	12	3597.23	2261.95	12	10
NE	10	1593.14	2202.32	12	9.74
E	10	1749.49	2418.46	12.5	9.85

Table 5: Current and proposed pipe sizes

Conclusions

Vflo® determined that the overland flow was different from the drainage flow. Considering these different directions of flow, the model did not represent the full amount of water that was traveling to these pipes in the storm-water drainage system. Because of this, rational method was used to determine the peak flows into the drainage network and specifically the points identified.

The proposed flood mitigation option would increase both the capacity of the system and prevent pluvial flooding. However, this option might be costly due to the large amount of pipes that would have to be used and the amount of excavation needed for the proposed detention. This suggests that one might have to look at other methods to reduce flood risk, such as flood proofing at the household level.

V. SITE 3: BRIAR PATCH

Site Overview and Model Setup

Briar Patch is a residential area within Buffalo Bayou watershed that constantly suffers from flooding problems. It is located south of Buffalo Bayou, just north of Briar Forest Dr. between

Eldridge Pkwy. And S. Dairy Ashford (see Figure 10). The size of this residential area is 72 acres and consists of 373 houses.

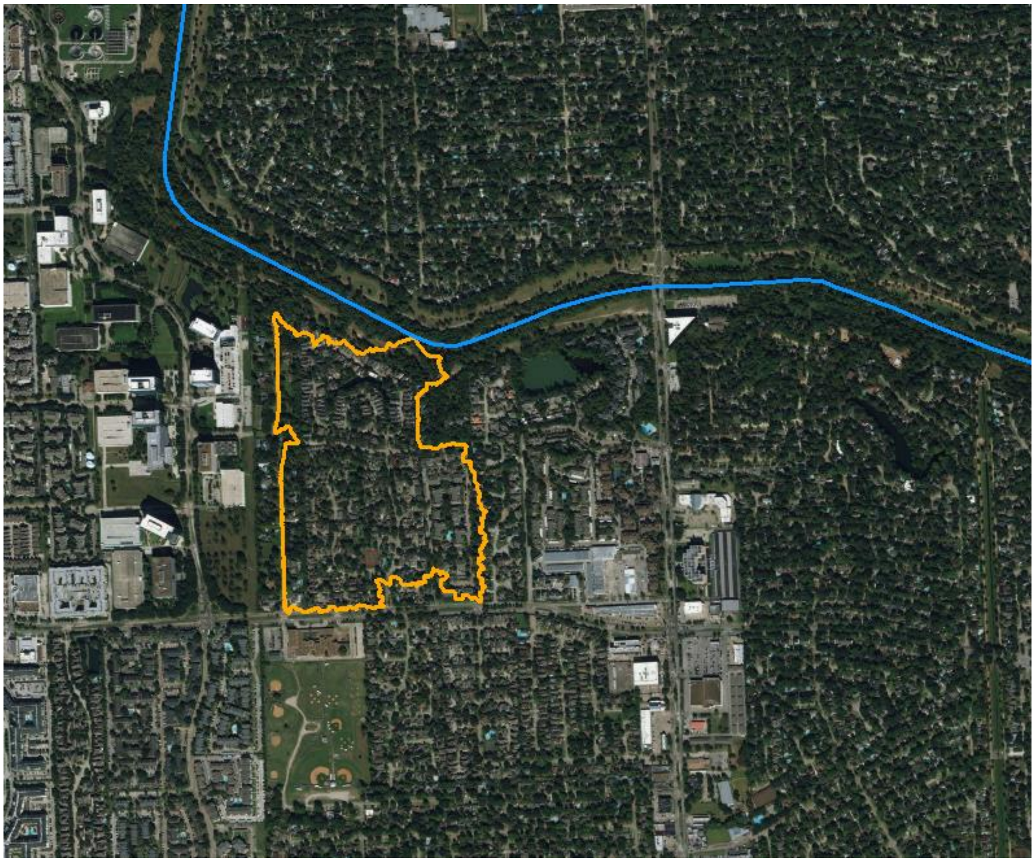

Figure 10: Briar Patch project location

A Vflo® model was developed for the project area by using available terrain, land use, and soils data. Two discharge points (outlets) into Buffalo Bayou were identified in the Vflo domain (see Figure 11). The two outlets coincided with two existing COH storm sewer pipes (48 in. and 72 in.). These outlets served as watch points for the subsequent hydrologic analysis.

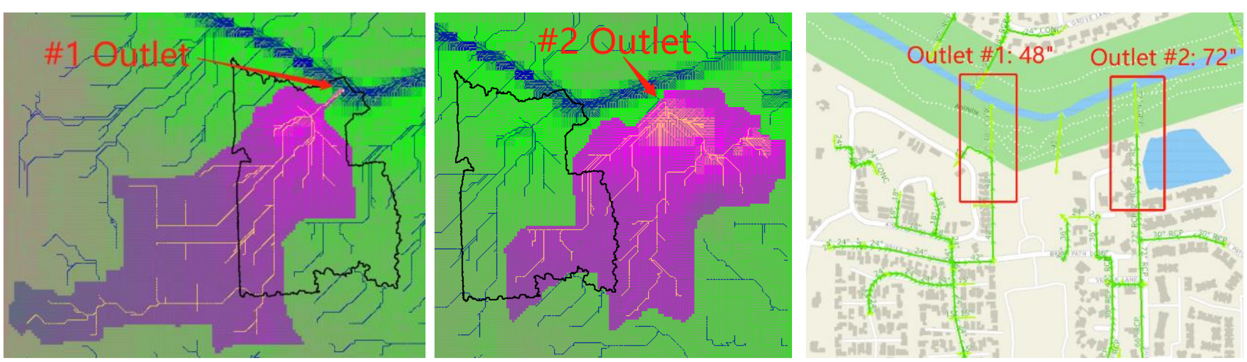

Figure 11: Vflo® outlets and contributing drainage areas (left and center); COH storm sewer network (right)

Hydrologic Analysis

The two contributing drainage areas delineated in Vflo® (Figure 11) covered over 90% of the Briar Patch study area. To better understand the existing hydrodynamics of the study area, surface runoff to the two previously mentioned outlets were computed in Vflo® under multiple design storms (i.e., 2-yr, 5-yr, 10-yr, and 100-yr). While the contributing drainage are to Outlet 1 is slightly larger than that to Outlet 2, overall their flow responses were comparable, with both having similar peak flows and runoff volumes for all simulated storms. These results suggest that the drainage area to Outlet 1 would be more flood vulnerable than the drainage area to Outlet 2, since the storm sewer pipe of Outlet 2 is significantly larger than that of Outlet 1 (72 vs 48 in.).

The peak flows at both outlets computed by Vflo® were used to determine whether the existing storm sewer pipes in each outlet would be able to adequately convey runoff from the various simulated storms, and whether any pipe replacements were necessary. As shown in Tables 6a and 6b, the existing storm sewer pipe of Outlet 1 is only able to convey up to a 5-yr storm. Meanwhile, the existing pipe of Outlet 2 could easily contain a 10-yr storm. In both cases, to be able to handle the 100-yr storms, the storm sewer pipes at both outlets would need to be enlarged to 84 in.

Return Period	2-yr	5-yr	10-yr	100-yr
Q (peak discharge) (cfs)	49.2	101.6	148.4	363.6
d (suggested diameter) (in)	36	48	54	84
d (existing diameter) (in)	48			

Table 6a: Pipe calculations for Outlet 1

Return Period	2-yr	5-yr	10-yr	100-yr
Q (peak discharge) (cfs)	62.4	110.7	149.8	349.1
d (suggested diameter) (in)	36	48	54	84
d (existing diameter) (in)	72			

Table 6b: Pipe calculations for Outlet 2

Flood Mitigation Analysis

Aside from the storm sewer drainage improvement option discussed in the previous section, the option of adding detention basins was considered. This option appears to be infeasible, however, since the study area and its immediate vicinity are virtually fully developed. Instead of adding new basins, a potential solution is to modify / improve the existing ponds in the area. Collectively, the existing basins totaled approximately 4.5 acres (see Figure 12), which could possibly be used to increase flood storage.

Figure 12: Briar Patch area (red) and existing detention (yellow)

Conclusions

The hydrologic analyses using Vflo® for the Briar Patch site, as well as the examination of existing drainage conditions reveal that the area draining to Outlet 1 is more flood vulnerable than the area draining to Outlet 2. Due to limited land availability, the options of adding more detention basins would be infeasible. Possible solutions include improving the existing storm sewer network and modifying existing basins to increase flood storage capacities. Individual home owners might also opt to flood-proof or elevate their houses.

VI. IMPLICATIONS AND FUTURE WORK

This project utilizes the distributed hydrologic model, Vflo®, as a tool to assess existing flood vulnerability at the site level in three Houston residential neighborhoods. This approach exposes local drainage issues, such as having inadequate pipe sizes to convey storm water. As demonstrated in this project, this methodology can be applied in any watershed or study area with sufficient spatial data, and is especially useful to assess flood vulnerability at the neighborhood scale. Future work could use the results computed by Vflo® to better inform and/or design local drainage networks and other flood control solutions. Additionally, Vflo® results could potentially be coupled with other hydraulic models to generate floodplain maps that better represent the actual flood risk of a watershed, and also be incorporated in other flood mitigation framework, such as a real-time flood warning system.