MEMORANDUM

City of Bellaire Master Drainage Concept Plan – Concept Plan Memorandum

For the City of Bellaire, Harris County Flood Control District, and Texas Department of Transportation
August 21, 2020 CI Job Num: 2019280-MDP-01 Task 002

This memorandum is to document the conceptual drainage plan as part of the overall Master Drainage Concept Plan (MDCP) within the City of Bellaire and sub-basin D115A (Cypress Ditch) which is tributary to Brays Bayou. This concept plan was developed in conjunction with the Team members, ARKK Engineers (ARKK), Costello, Inc. (CI), and Freese and Nichols (FNI) to determine the required main trunk infrastructure necessary to reduce the localized flooding within the City of Bellaire for both the 10 and 100-year storm events. This addresses the drainage improvements necessary to convey stormwater to Brays Bayou via the internal drainage system and Cypress Ditch. Even with improved local drainage systems, flooding conditions along Brays Bayou could still impact areas within the city regardless of the internal improvements.

1. SCOPE OF WORK

Below is a summary of the scope of work addressed in this concept plan:

1. Determine improvements for two design storm scenarios: Atlas 14 10- and 100-year storm events
2. Determine 3 alternatives for improvements to main stormwater trunk systems to convey the above peak flows will maintaining final hydraulic grade lines below the existing right-of-way natural ground elevations at major collection locations.
3. Determine various improvements alternatives to convey the peak flows to Brays Bayou. This includes evaluating open channels, storm sewers, detention ponds, and flood tunnels.
4. Determine estimated mitigation volume for the improved conveyance alternatives so as to not impact the peak flows along Brays Bayou
5. Review and analyze potential overflows occurring into the City limits from Chimney Rock (and possibly further west) and from the W111-11-11 across Westpark
6. Provide a summary memorandum of the above along with initial cost estimates of each alternative.

2. MAIN TRUNK ROUTE ANALYSIS

An analysis was done to develop conceptual alignment corridors to improve the main trunk systems such that the design storm event rainfall could be conveyed to Bray's Bayou while containing any inundation within the right-of-way to mitigate structural flooding. A review of the overall topography and previous studies were utilized to determine generalized overland sheetflow paths. The areas with sheet flow were compared to the existing main trunk drainage system which runs north south along the major roadway arterials (Rice, I610, Newcastle) before discharging into Cypress Ditch. The topography within the City results in sheetflow traveling from west to east and then concentrating along the Union Pacific railroad track east of I610 along the east boundary of the city. The conceptual alignment corridors investigated looked at ways to follow the general sheetflow pattern and intercept flow to Cypress Ditch to reduce or eliminate additional sheetflow from traversing west to east.

A. CONCEPTUAL ALTERNATIVES ANALYSIS

An analysis was performed where multiple conceptual alignments and improvements alternatives were considered. The project team performed a high-level review of each solution based on effectiveness, constructability, total project cost, and potential impact to residents.

A brief description of each one is provided below:

1. Existing Drainage Collection Systems Route:

Maintaining the existing drainage areas and upsizing each north south system to handle the localized runoff. This requires the Rice trunk system to be sized to capture additional sheetflow from the west.

2. Newcastle Collection Route

This option consolidates the systems to better follow existing topography for an outfall into Cypress Ditch. This includes an improvement alternative that intercepts flows from north of Bellaire Boulevard along I610 and directed to an improved Newcastle system. The Rice Storm Sewer would be improved to convey the localized and any sheetflow south of Bellaire Boulevard.

3. Railroad Collection Route:

This option consolidates the drainage system to a single conduit along the railroad track on the east boundary of the City. A large storm sewer or tunnel would be constructed along Bellaire Boulevard to intercept runoff from north portion of the City and convey to a north-south conduit system along the railroad track. This north-south conduit could be a new flood control channel, expansion of the Kilmarnock Ditch west of the railroad, or a tunnel parallel to the railroad. The South Rice and I610 systems would then be improved for their own localized drainage area south of Bellaire Boulevard.

4. I610 Route:

This option utilizes a conduit along the west bound I610 frontage road that utilizes the natural restriction created by the I610 mainlanes to collect runoff and convey to Brays Bayou. For a possible tunnel solution, an existing regional detention pond south of Brays Bayou at I610 or a possible proposed HCFCD basin site could be used as the tunnel discharge location. For the storm sewer improvements, the system along 610 would discharge into Cypress Ditch. This system would be designed such that there was no overflow across I610 during a design storm event allowing the system east of I610 to be designed for its local drainage area only.

B. RECOMMENDED CONCEPTUAL ALIGNMENTS

Based on the project team review, the Railroad Collection Route, I610 Route, and existing drainage system conceptual alignments are recommended for further analysis. These three concepts provide improvements that have the highest potential to achieve the project goals while still maintaining reasonable construction cost expectations. Each concept was assigned a designation for further evaluation.

Concept A is the Railroad track option provides the route that most closely follows the natural sheetflow drainage patterns and allows for conveying runoff as efficiently as possible to Brays Bayou. This concept includes a major drainage collection system generally parallel to the railroad tracks to convey water to Cypress Ditch. Concept B is the I610 route allows for sheetflows to be captured and conveyed directly to Brays and has the potential to significantly mitigate flooding in the City's east side of the city by reducing the sheetflow crossing I610. Additionally, the area west of I610 will also benefit by capturing sheetflow from Chimney Rock and reducing the overall flooding depths to within the rights-of-way. Concept C utilizes the existing drainage ways and enlarges each individual system to collect the runoff and convey to Cypress Ditch. In all concept options, tributary collector systems will be required to capture and convey water to the main trunk. This analysis assumes that the tributary systems will generally be storm sewers constructed as part of street reconstruction projects.

3. HYDROLOGIC AND HYDRAULIC ANALYSIS

The following methods and procedures were utilized to determine the runoff and hydraulic capacity of the conceptual alignments.

A. PEAK FLOW COMPUTATIONS

To determine required sizing of proposed elements of each improvement concept, peak flows were computed at major collection points within the study area. The D115A sub-basin boundary was sub-divided based on the overall major storm sewer service areas developed by the City in previous studies. These service areas were further sub-divided to individual drainage areas to allow for computation of peak flows at hydrologic nodes at both major points of interest and at major flow change locations along the proposed concept alignments. A drainage area map of the subdivided D115A sub-basin is provided on **Exhibit 2**. Individual drainage area parameters utilized in the overall analysis are provided on **Table 1**.

Table 1 – Individual Drainage Area Rational Parameters

Drainage Area	MPE	Area (ac)	TC (min)	C-Value
R-1	50.5	94.6	29.8	0.46
R-2	51.6	155.0	51.0	0.44
R-3	52	204.2	57.9	0.52
R-4	53	172.1	34.9	0.51
610-1	48.5	154.6	51.3	0.47
610-2	49.5	125.8	33.7	0.47
610-3	50.1	242.2	60.9	0.50
610-4	50.6	239.6	37.5	0.51
N-1	47	173.8	34.1	0.46
N-2	47.1	168.6	29.2	0.45
N-3	49.2	193.6	58.1	0.47
N-4	51.5	225.1	30.1	0.69
F-1	50.5	103.4	33.8	0.46
E-1	48.5	56.9	26.1	0.45

To determine the peak flow at the hydrologic nodes, the upstream contributing drainages areas composite landuse parameters were computed on an area weighted average and the total travel time was computed for the entire upstream drainage area. The Rational Method was utilized to compute peak flow rates for the 10 and 100-year storm events as the drainage areas are generally 200 acres and less and the primary conveyance features are large underground storm sewer systems. The NOAA Atlas 14 Intensity-Duration-Factors from the TxDOT Houston district were utilized to compute intensities along the proposed routes, as shown on **Table 2** below.

Table 2 – TxDOT Harris County Rainfall Intensity-Duration-Frequency Coefficients

Coefficient	Design Annual Exceedance Probability (Design Annual Recurrence Interval)						
	50% (2-year)	20% (5-year)	10% (10-year)	4% (25-year)	2% (50-year)	1% (100-year)	0.2% (500-year)
e	0.8004	0.7652	0.7458	0.7247	0.7091	0.6963	0.6878
b	64.7650	75.5205	84.1543	95.8918	103.8089	113.6760	156.5886
d (min)	12.8285	12.4064	12.3545	12.5119	12.6173	13.1642	17.3069
Intensity (inches/hour)	5.30	6.99	8.29	10.04	11.37	12.75	16.10

B. MAXIMUM PONDING ELEVATION (MPE)

For each drainage area, a review of the 2018 HGAC LiDAR dataset was performed to determine the lowest natural ground elevation that would generally result in no ponding outside of a road right-of-way. Each drainage area's lowest topographic location was identified and then a review of the surrounding area completed to determine the corresponding maximum ponding elevation (MPE) for that drainage area, as shown on **Exhibit 2**. These elevations will be utilized to compute system capacity such that the maximum peak water surface elevation for the design storm event does not exceed the MPE at that location. Maintaining design water surface elevation (WSE) at or below the MPE will generally assume the in the design storm event no structures would be flooded due to the capacity of the system.

C. POTENTIAL OVERFLOWS (CHIMNEY ROCK AND WESTPARK)

A review of the existing topographic data indicates that there are large areas of sheetflow that can enter the city from the west (generally from the Chimney Rock system) and the north along the Westpark Drive area. In recent large rain events, sheetflow was visually observed entering the D115A sub-basin from the Chimney Rock system.

1. Chimney Rock Overflows

A review of the topography indicated that sheetflow can enter along the entire west boundary of the City. A review of the COH GIMS 2008 flowpath patterns show concentration of sheetflow north of Bellaire Boulevard in the vicinity of the Bissonnet/I610 intersection traverses south down the I610 southbound frontage road and then under I610 at the Evergreen intersection. This was further confirmed by comparison to the HGAC 2018 LiDAR dataset and analyzing overland flowpath routes. Following the COH flowpath analysis, there could be contributing sheetflow as far as US 59 that can travel to Bellaire. Preliminary results from the COH Chimney Rock analysis indicates that in the 100-year storm event (not the updated Atlas 14 100-year) that there was approximately 600 cfs that could overflow the Chimney Rock system and enter Bellaire. A preliminary rain-on-grid sheetflow model was developed in HEC-RAS 2D that indicated in the Atlas 14 100-year there was approximately 1,200 cfs entering north of Bellaire Boulevard and 600 cfs entering south of Bellaire Boulevard. To account for this overflow in the hydraulic sizing, the preliminary sheetflow peak flow rates identified in the preliminary rain-on-grid model were manually added to the hydrologic peak flow rates to account for the potential overflows. **Table 3** below provides the flow rates used for both storm events for both north and south of Bellaire

Table 3 – Preliminary West Overflows from Chimney Rock System: Computed from Preliminary Unsteady HEC-RAS 2D model of Project Brays

Location	10-Year	100-Year
North of Bellaire Blvd.	600	1200
South of Bellaire Blvd.	0	600

2. Westpark Overflow
Along the north boundary of the city, there is the potential from W129-01-00 to overflow the natural ground and enter the Newcastle areas during extreme rain events. A review of the topographic data was performed and compared to the 100-year HGL depicted on the HCFCD W129-00-00-C003 construction plans dated July 2017. The plans listed a 100-year HGL of 54.5 ft on the plan and profile at the north bound frontage road. A profile from the 2018 LiDAR dataset indicates a low point of 55.7 ft. Further analysis will be needed to determine what the potential Atlas 14 100-year peak WSE would be based on the new improvements.

D. HYDRAULIC ANALYSIS

Each Concept was evaluated utilizing the runoff computations and MPE identified above. The proposed concepts were sub-divide into reaches based on major hydrologic node locations. Cumulative peak flows were computed at each of these nodes and culverts sized to provide the conveyance necessary to maintain the computed hydraulic grade line at the desired elevations. The upstream and downstream MPE for each reach was utilized to determine the available hydraulic grade line slope. Manning's equation was used with the available HGL slope and peak flow rates for the design storm to determine the required drainage infrastructure required to provide the conveyance for that reach.

Each segment was evaluated for both traditional underground storm sewer culverts and for a tunnel option operating as an inverted siphon. Additionally, Concept A Newcastle Reach from Bellaire Boulevard to Newcastle was evaluated for a potential flood control channel. Each concept was evaluated for two levels of service, 10 and 100-year Atlas 14, and then with and without overflow from the Chimney Rock system.

4. DETENTION MITIGATION ANALYSIS (BRAY'S BAYOU)

The proposed improvements will require detention mitigation volume to be provided either within the system or in a separate detention facility to reduce the increase in peak flow associated with the improvements so as to not impact the peak water surface elevations along Brays Bayou. To estimate a required detention mitigation volume, the preliminary HCFCD Basin Development Factor methodology was utilized. A pre- and post-improved hydrograph was computed for the D115A sub-basin using the BDF parameters that represent the current drainage conditions within the sub-basin. The BDF Line and BDF landuse parameters were both modified to reflect a fully improved system which will estimate the post-project peak flow rate into Brays Bayou.

- In the existing condition, the BDF landuse was assumed to be "Curb-and-Gutter with Storm Sewer Pre-1987." In the improved condition, the landuse was assumed to be "Curb-and-Gutter with Storm Sewer Post-1987."
- In existing, approximately 60% of the flowpath was considered as "Natural Channel" to reflect the overland sheetflow from north to south, with the remaining flowpath considered as Concrete which

reflected Cypress Ditch. In proposed, the entire flowpath was considered as "Concrete" to reflect a drainage system that would convey the entire 100-year flow as either storm sewer, tunnel, or channel.

- The remaining sub-unit hydrograph parameters remained constant between existing and proposed.

Table 4 depicts the parameters utilized in the analysis to develop both the pre- and post-project hydrographs. Clarks Unit Hydrograph parameters were input into HEC-HMS and simulated for the effective 10, effective 100, and Atlas 14 100-year storm events. The pre and post hydrographs were compared in excel and the delta in volume was computed to estimate minimum detention volume required to mitigate the improvements. **Table 4** below depicts the estimate mitigation volume necessary for each design storm event so no flow impacts would occur to Brays Bayou due to the improvements.

Table 5 – Estimated Mitigation Volumes for Design Strom Events

Condition	24-Hour Rainfall (inches)	Mitigation Volume (acre-feet)
Effective 10-year	7.6	332.9
Effective 100-year	13.2	605.8
Atlas 14 100-year	16.9	783.4

The detention volume can be provided in various ways. The proposed major trunk line improvements can be increased to allow for mitigation to occur within the system, potential deepening/widening of Cypress Ditch, inline detention along Kilamonock ditch, detention basin along Cypress Ditch/Brays, or some combination thereof. For this analysis, two detention alternatives were investigated: 1) increasing the proposed trunklines to provide detention volume and 2) providing a separate detention basin along Bray's Bayou. Both options assume that Cypress Ditch would be improved to the extent possible to maximize the available detention volume within the existing right-of-way.

A. MAIN TRUNK AND CYPRESS DITCH DETENTION

The proposed trunk lines were increased to provide the total detention volume identified from above. Upstream of I610, Cypress Ditch can be deepened to a concrete slope paved vertical wall cross section to provide a maximum of approximately 109 acre-feet of volume. The remaining 625 acre-feet was assumed added to the major trunkline systems. The proposed storm sewer volume for each Concept was computed based on the 100-year, Cypress Overflow condition. Generally, the proposed systems would provide the detention volume for the 10-year storm event and would need to be increased to provide the remaining mitigation volume needed for the Atlas 14 100-year storm event. The storm sewer systems as currently proposed would need to increase by an average of 40% in size to provide the full Atlas 14 100-year mitigation volume within the system. Inline mitigation in the tunnel concept would need to be evaluated as the overall cross-sectional area may lower velocities and induce sediment.

B. DETENTION BASIN AND CYPRESS DITCH

A detention pond was sized that would provide the mitigation volume need for each storm event. This basin sizing assumed that Cypress Ditch improvements would provide the 109 acre-feet available as described above. The average natural ground along Cypress Ditch is elevation 48 and the flowline of Brays is approximately 21 at the confluence of Cypress Ditch. This produces a maximum 27-feet of depth available for detention storage. For this analysis, 15-feet of depth is utilized to account for unforeseen conflicts that may limit utilizing the full depth available. The detention pond is assumed to be 4:1 side slopes, dry bottom pond, with 30-foot maintenance berms. **Table 6** below depicts an estimated pond top area needed for each corresponding design storm event.

Table 6 – Estimate Regional Mitigation Pond Size for Each Design Storm Event

Condition	Mitigation Volume (acre-feet)	Cypress Ditch Add. Volume (acre-Feet)	Remaining Volume Req.	Pond ROW Req. (acres)	Estimated Cost (MM)
Effective 10-year	332.9	109	223.9	24	$13.9
Effective 100-year	605.8	109	496.8	49	$22.3
Atlas 14 100-year	783.4	109	674.4	65	$29.8

5. CONCEPTS ALIGNMENTS AND COST ESTIMATES

The two recommended concept alignments were further detailed to estimate required sizes for the individual components of each. The concepts were evaluated for both design storm events and both with/without overflow from Chimney Rock. Each major route element was evaluated as applicable for different improvement types to include storm sewer, open channel, and tunnels. Concept layouts of each drainage element along the route is provided on **Exhibit 3-A** for Concept A, **Exhibit 3-B** for Concept B, **Exhibit 3-C** for Concept C. A summary of the size and type of each element along with a total estimated cost is provided on **Table 7**.

To evaluate the overall project cost, quantities were computed for each alignment with the below assumptions:

- Storm Sewer Cost Estimates: Assumed an average $2000 per linear foot for roadway and utility conflict relocation as estimated from recent municipal roadway reconstruction projects. Storm Sewer cost estimated using linear footage of the proposed culvert sizes.
- Channel Cost Estimates: Total volume estimated by the proposed cross-sectional area and assuming all haul off of material. Right-of-way cost estimated by evaluating proposed ROW width in ArcGIS for each concept and determining number of properties impacted. Each property assumed to be acquired at $525,000 per tract based on an average cost from Harris County Appraisal District Data.
- Tunnel Cost Estimates: Assumed a single tunnel size for each major reach and then cost per linear foot. A detailed narrative of the concept design and construction has been provided in the attached memorandum from Freese and Nichols dated July 24, 2020.
- Due to the high-level nature of this analysis, a construction cost contingency of 50% has been applied to all concepts. An estimated engineering budget for planning, design, and construction administration has been assumed at 20% of the construction cost.

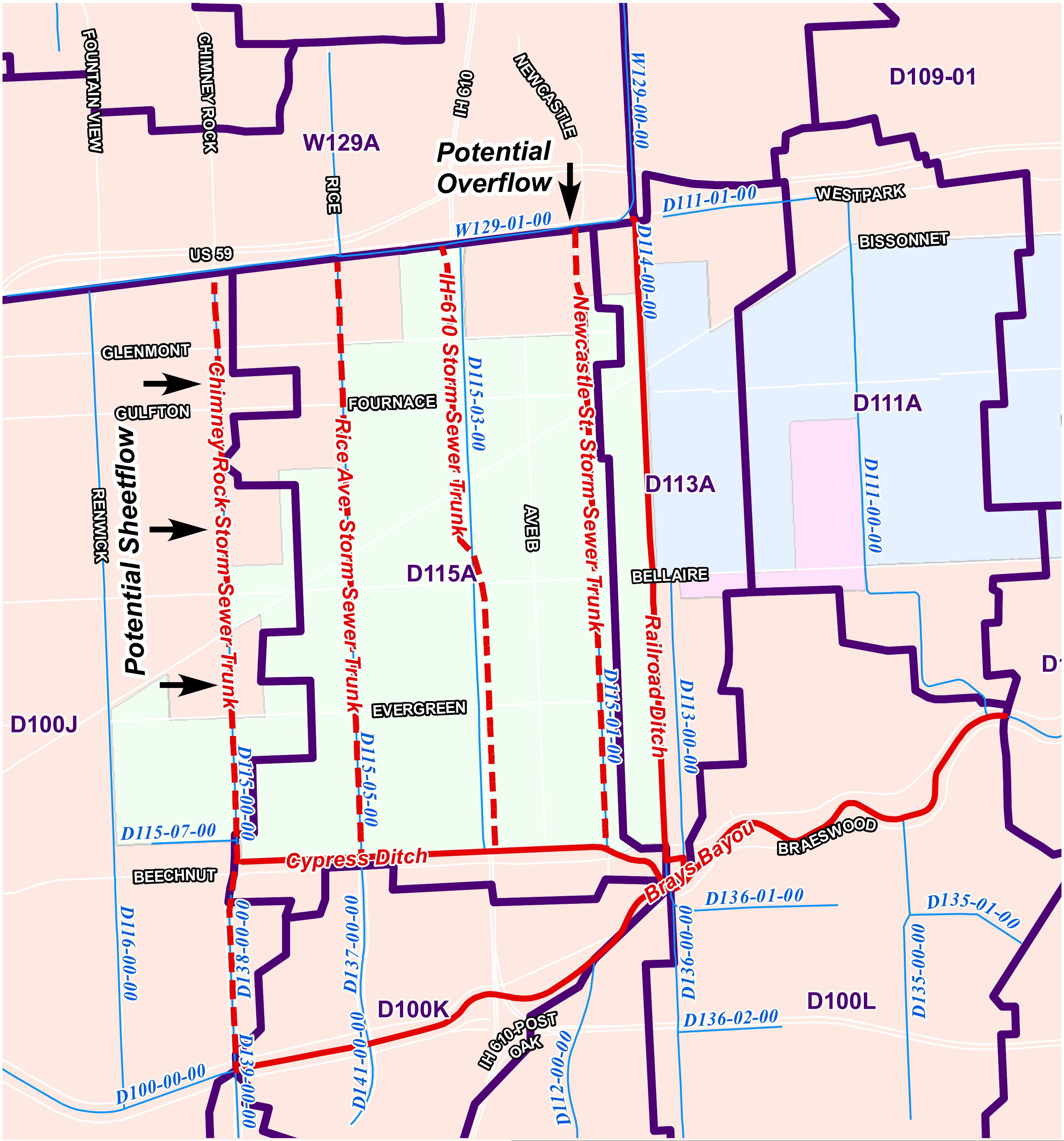
6. REVIEW OF CONCEPT ALIGNMENTS

A review of the three Concepts indicates a range of cost for a 10-year level of service of $396MM for Concept A and a maximum of $603MM for Concept B. 100-year flood reduction ranges from $633MM to $900MM. Additional mitigation cost will be required to ensure no adverse impacts to Brays Bayou from improvements. A summary of each Concept along with costs and pros and cons is provided in the Table Below:

Concepts	Range of Cost (in Millions)	Pros	Cons
Concept A	10-YR $362 to $549 100-YR $633 to $681	• Follows Natural Topography • Collects extensive floodwaters along the railroad tract • Provides Most Cost-Effective Option for 100-year • Improvements can be Phased, spreading out cost • Removes drainage area from Cypress Ditch	• Moderately Disruptive to roadways and utilities • The channel option would require purchase of properties
Concept B	10-YR $461 to $603 100-YR $703 to $900	• Least Disruptive to roadways and utilities • Collects floodwaters from east of I610 and conveys them directly to Brays. • Does not require Cypress Ditch improvements	• Cannot be Phased, all tunnel cost will need to be constructed upfront • Requires tunnel under I610 right-of-way • Requires some property acquisition for entry shafts • Requires localized collector systems to convey floodwaters to tunnel
Concept C	10-YR $405 to $524 100-YR $687 to $801	• Can be multi-phased and improvements be constructed independently of each system • Can provide both major flooding reduction but also direct local street flooding reduction.	• Most Disruptive to roadways and utilities • Would require additional capacity for Cypress Ditch • Would require rebuilding the major North-South tributaries

In reviewing the overall cost, the channel will provide the most cost-effective flood reduction in both the 10 and 100-year event but requires significant property acquisition. The tunnel option provides the least construction disturbance but is not as cost effective as the storm sewer systems in the 10-year event. As the level of service requirement increases, the cost efficiency increase of the tunnel results in a lower overall cost and a more cost-effective option.

Based on the review, the three Concepts are recommended for further detailed analysis in the advanced hydraulic models being developed of the City of Bellaire Drainage system.



Legend

- Study Reaches - Underground
- Study Reaches - Channel
- Stream Centerline
- TSARP Catchment
- City of Bellaire
- City of Houston
- City of West University
- City of Southside Place

N

0 3,000

Feet

1 in = 3,000 ft

Costello

Costello, Inc.
Engineering and Surveying
TBPE Firm Registration No. 280

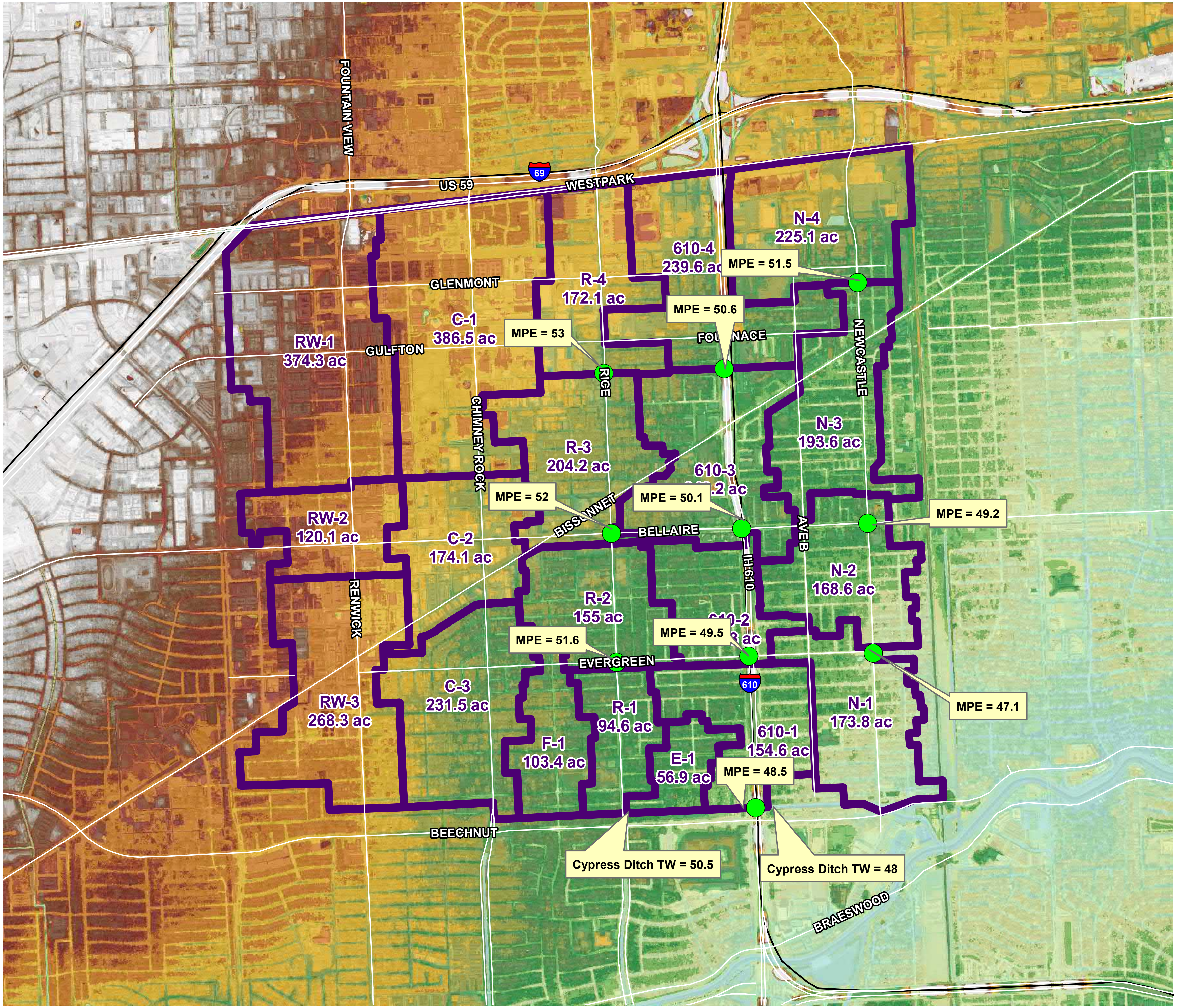
CITY OF BELLAIRE MDP

STUDY AREAS

JOB NO.: P000015-000-00	DATE: AUG 2020	BY: JG

EXHIBIT 1

Date Saved: 8/21/2020 8:32:19 AM V:\Bellaire\300_Drainage Anaysis\303 (Master Drainage Plan)\Concept Memo\EX1 Bellaire MDP Study Reaches.mxd



N

0 2,000

Feet

1 in = 2,000 ft

Legend

Roads

MPE Nodes

Existing Drainage Areas

Major Highways

I

US

SH

FM

Costello, Inc.
Engineering and Surveying
TBPE Firm Registration No. 280

BELLAIRE MASTER DRAINAGE PLAN
CONCEPT DESIGN

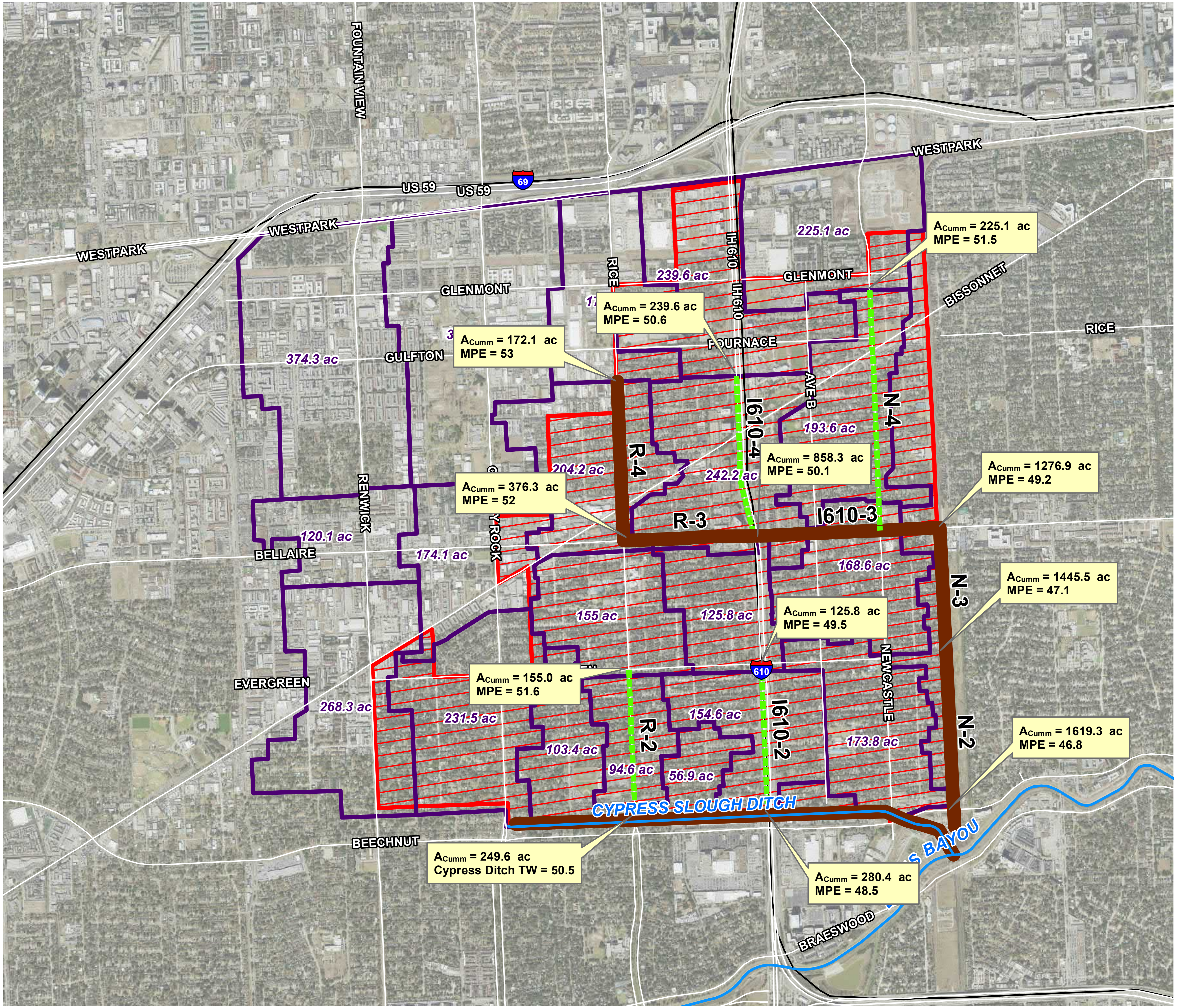
DRAINAGE AREAS & MAXIMUM PONDING ELEVATIONS

JOB NO.: 2019280-MDP-01	DATE: MAR 2020	BY: CRC

EXHIBIT 2

V:\Bellaire\300_Drainage Anaysis\303 (Master Drainage Plan)\Concept Memo\Overall\GIS\MPE Exhibit.mxd

Date Saved: 7/10/2020 8:28:13 AM



N

0 2,000
Feet
1 in = 2,000 ft

Legend

Roads

Stream_Centerline

Class

Major Collector

Minor Collector

Bellaire City Limits

Existing Drainage Areas

Major Highways

I

+1,200 CFS FOR SHEET FLOW
PER COH CHIMNEY ROCK ANALYSIS

Costello

Costello, Inc.
Engineering and Surveying
TBPE Firm Registration No. 280

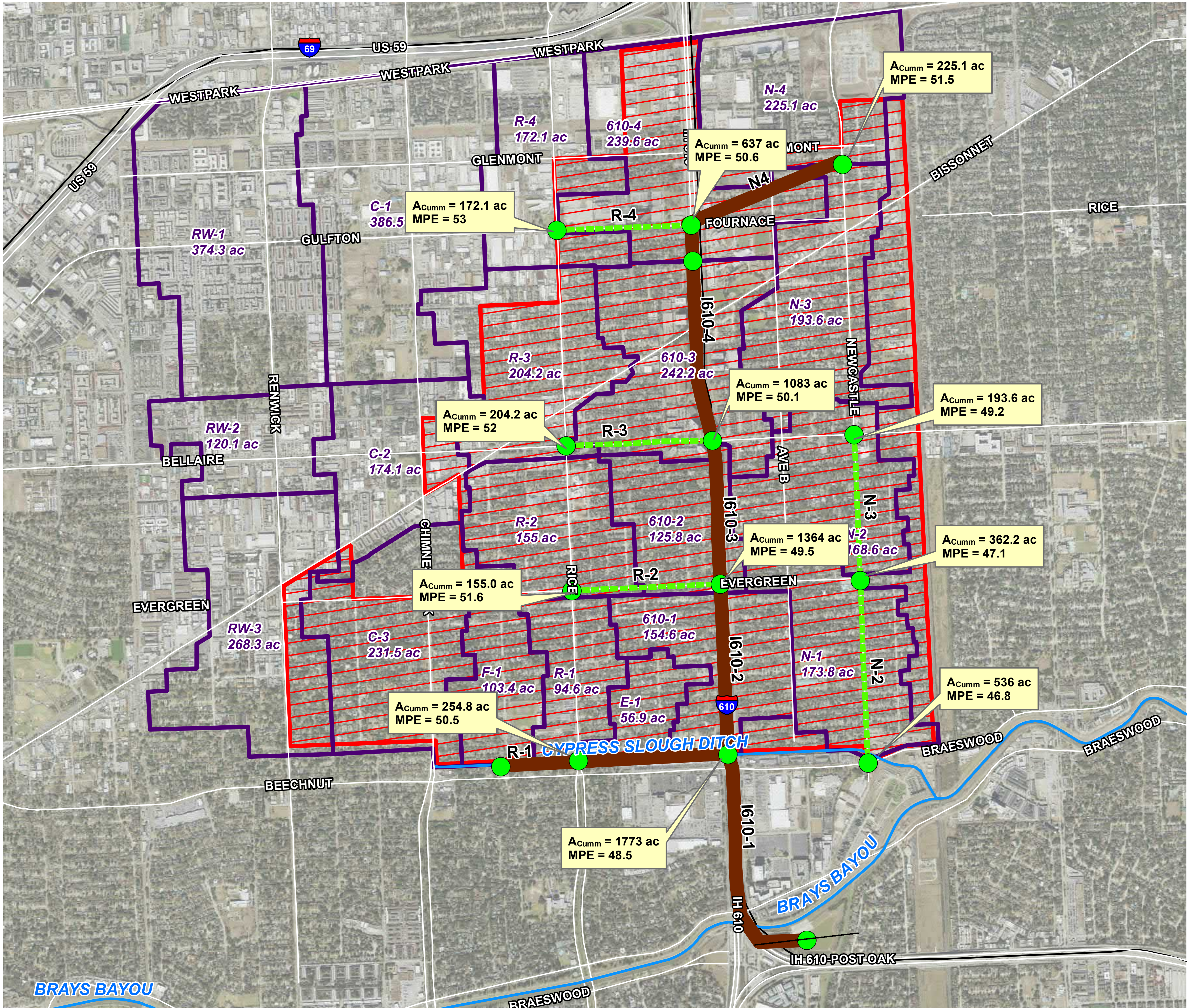
BELLAIRE MASTER DRAINAGE PLAN
CONCEPT DESIGN

CONCEPT A

JOB NO.:2019280-MDP-01-002	DATE: APR 2020	BY: JSW

EXHIBIT 3-A

Date Saved: 7/10/2020 8:31:18 AM V:\Bellaire\300_Drainage Anaysis\303 (Master Drainage Plan)\Concept Memo\Concept A\Concept A.mxd



N

0 2,000

Feet

1 in = 1,800 ft

Legend

AltB-Nodes

AltB-Alignments

Major Collector

Minor Collector

Stream_Centerline

Roads

Major Highways

I

Existing Drainage Areas

Bellaire City Limits

+1,200 CFS FOR SHEET FLOW
PER COH CHIMNEY ROCK ANALYSIS

Costello, Inc.
Engineering and Surveying
TBPE Firm Registration No. 280

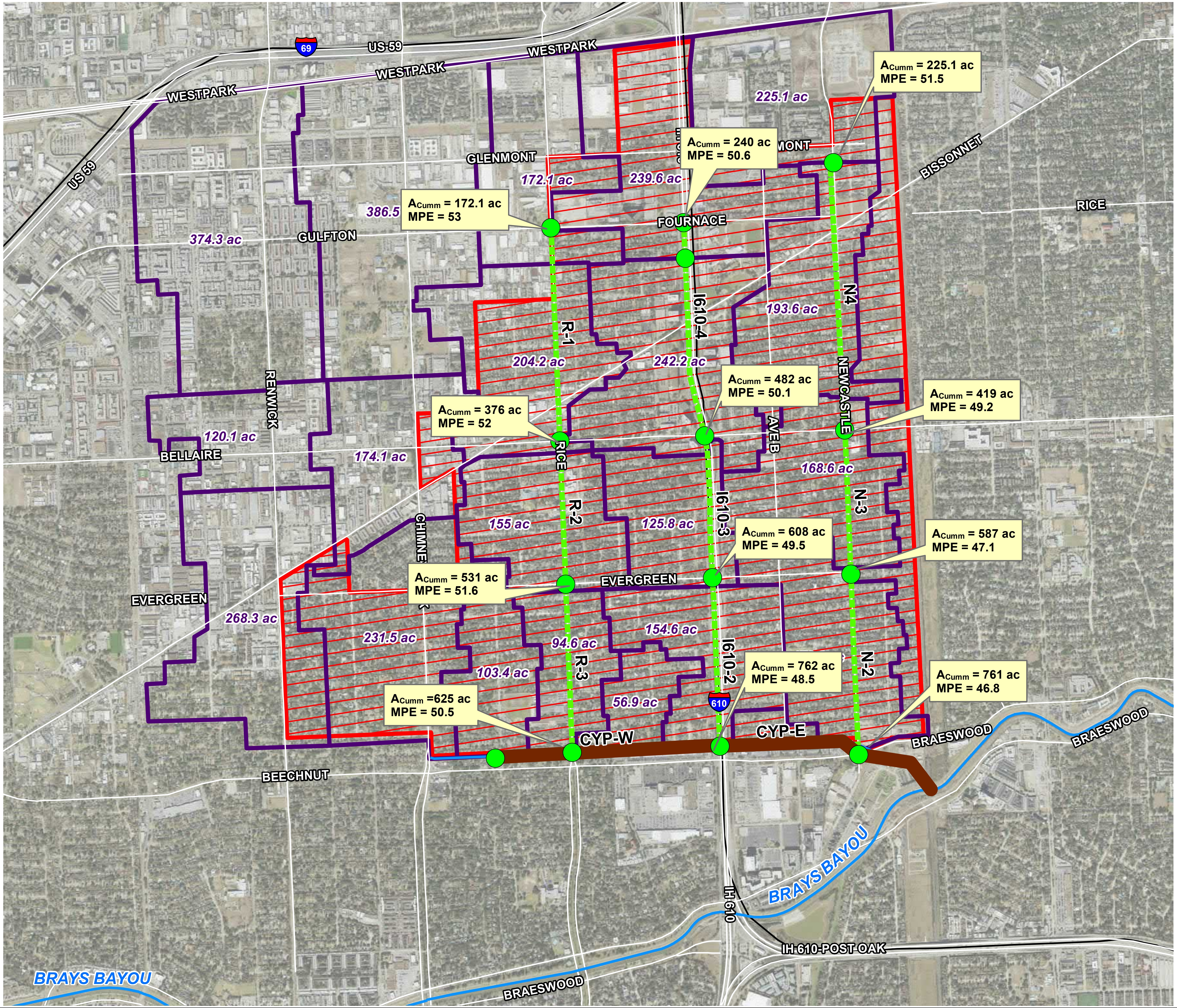
BELLAIRE MASTER DRAINAGE PLAN
CONCEPT DESIGN

CONCEPT B

JOB NO.:2019280-MDP-01-002	DATE: MAR 2020	BY: CRC

EXHIBIT 3-B

Date Saved: 7/10/2020 8:32:56 AM V:\Bellaire\300_Drainage Anaysis\303 (Master Drainage Plan)\Concept Memo\Concept B\Concept B Exhibit.mxd



N

0 2,000

Feet

1 in = 1,800 ft

Legend

ConC_Nodes

Class

Major Collector

Minor Collector

Stream_Centerline

Roads

Major Highways

I

Existing Drainage Areas

Bellaire City Limits

+1,200 CFS FOR SHEET FLOW
PER COH CHIMNEY ROCK ANALYSIS

Costello

Costello, Inc.
Engineering and Surveying
TBPE Firm Registration No. 280

BELLAIRE MASTER DRAINAGE PLAN
CONCEPT DESIGN

CONCEPT C

JOB NO.:2019280-MDP-01-002	DATE: MAR 2020	BY: CRC

EXHIBIT 3-C

V:\Bellaire\300_Drainage Anaysis\303 (Master Drainage Plan)\Concept Memo\Concept C\Concept C Exhibit.mxd

Date Saved: 7/10/2020 8:33:59 AM

Table 4
Bellaire MDCP

D115A

Subbasin	Drainage Area (acres)	Drainage Area (sq.mi.)	Channel Improvements (Total Lengths or Percent): Natural Channel	Channel Improvements: Improved	Channel Improvements: Concrete	Weighted Conveyance BDF	Undeveloped: Area (ac)	Undeveloped: BDF	Open Space: Area (ac)	Open Space: BDF	Developed Roadside Ditch: Area (ac)	Developed Roadside Ditch: BDF	Developed Storm Sewer Pre 1987: Area (ac)	Developed Storm Sewer Pre 1987: BDF	Developed Storm Sewer Post 1987: Area (ac)	Developed Storm Sewer Post 1987: BDF	AREA CHECK
D115A_Ex	2384.0	3.725	11727	0	9263	2.65		0.0	0.0	1.0	0.0	1.5	2384.0	3.0	0.0	6.0	0.0
D115A_Prop	2384.0	3.725	0	0	20990	6.00		0.0	0.0	1.0	0.0	1.5	0.0	3.0	2384.0	6.0	0.0

(Land Classification Areas: Undeveloped through AREA CHECK)

Subbasin	Land Use BDF	Composite BDF	Tc (Unadjusted)	R (Unadjusted)	Channel Slope(ft./mi) S	Overland Slope(ft./mi.) So	SxSo	Slope Adj K_s	Watershed Detention Volume not Modeled Directly (ac-ft)	Detention Rate DR	Detention Adj C_f	Percent Ponding DPP	Percent Impervious 2018	TC'' (Slope and Detention Adjusted)	R'' (Slope and Detention Adjusted)	Ponding Adjustments for Storage Values (R''): 20% (5-Yr)	10% (100-Yr)	4% (25-Yr)	2% (50-Yr)	1% (100-Yr)	0.2% (500-Yr)
D115A_Ex	3.00	5.6	3.07	7.10	3.70	10.00	37.00	0.94	0.0	0.00	1.00	0	59.9	2.88	6.67	6.67	6.67	6.67	6.67	6.67	6.67
D115A_Prop	6.00	12.0	1.94	3.39	3.70	10.00	37.00	0.94	0.0	0.00	1.00	0	59.9	1.82	3.18	3.18	3.18	3.18	3.18	3.18	3.18

TABLE 7

Concept A - Railroad Track Route Summary

			10-YR With Chimney Rock Overflow				10-YR Without Chimney Rock Overflow		
Element	**Length (feet)**	**Q (cfs)**	**Storm Sewer**	**Channel**	**Tunnel**	**Q (cfs)**	**Storm Sewer**	**Channel**	**Tunnel**
R4	3,430	415	3- 9x6 RCB	3- 9x6 RCB	12-FT DIA	415	3 - 9x6 RCB	3 - 9x6 RCB	12-FT DIA
R3	2,800	1283	3- 10x8 RCB	3- 10x8 RCB	16-FT DIA	683	3 - 9x6 RCB	3 - 9x6 RCB	12-FT DIA
I610-4	3,420	562	3- 10x8 RCB	3- 10x8 RCB	16-FT DIA	562	3 - 10x8 RCB	3 - 10x8 RCB	16-FT DIA
I610-3	3,840	2101	5 - 12x10 RCB	5 - 12x10 RCB	25-FT DIA	1501	5 - 10x10 RCB	5 - 10x10 RCB	22-FT DIA
N4	4,900	803	2 - 10x10 RCB	2 - 10x10 RCB	2 - 10x10 RCB	803	2 - 10x10 RCB	2 - 10x10 RCB	2 - 10x10 RCB
Railroad Track (N - 1, 2,and 3)	6,700	2827	4 - 12x12 RCB	200-FT ROW	25-FT DIA	2227	4 - 12x12 RCB	190-FT ROW	22-FT DIA
R2	3,100	260	1 - 10x8 RCB	1 - 10x8 RCB	10-FT DIA	260	1 - 10x8 RCB	1 - 10x8 RCB	10-FT DIA
R1	300	367	1 - 10x10 RCB	1 - 10x10 RCB	10-FT DIA	367	1 - 10x10 RCB	1 - 10x10 RCB	10-FT DIA
I610-2	3,250	504	1 -10x8 RCB	1 -10x8 RCB	13-FT DIA	504	1 -10x8 RCB	1 -10x8 RCB	13-FT DIA
E-1	1,800	142	1 - 10x7 RCB	1 - 10x7 RCB	1 - 10x7 RCB	142	1 - 10x7 RCB	1 - 10x7 RCB	1 - 10x7 RCB
F-1	1,800	230	1 - 12x10 RCB	1 - 12x10 RCB	1 - 12x10 RCB	230	1 - 12x10 RCB	1 - 12x10 RCB	1 - 12x10 RCB
Cost Estimate			**$396,000,000**	**$550,000,000**	**$549,000,000**		**$384,000,000**	**$535,000,000**	**$501,000,000**

			100-YR With Chimney Rock Overflow				100-YR Without Cypress Overflow		
Element	**Length (feet)**	**Q (cfs)**	**Storm Sewer**	**Channel**	**Tunnel**	**Q (cfs)**	**Storm Sewer**	**Channel**	**Tunnel**
R4	3,430	838	2 - 11x10 RCB	2 - 11x10 RCB	17-FT DIA	838	2 - 11x10 RCB	2 - 11x10 RCB	17-FT DIA
R3	2,800	2613	4 - 12x10 RCB	4 - 13x10 RCB	22-FT DIA	1413	2 - 12x10 RCB	2 - 13x10 RCB	17-FT DIA
I610-4	3,420	1139	4 - 12x10 RCB	4 - 12x10 RCB	22-FT DIA	1139	4 - 12 x 10 RCB	4 - 12 x 10 RCB	22-FT DIA
I610-3	3,840	4311	7 - 12x12 RCB	7 - 12x12 RCB	30-FT DIA	3111	8 - 12X10 RCB	8 - 12X10 RCB	30-FT DIA
N4	4,900	1611	3 -12x10 RCB	3 -12x10 RCB	3 -12x10 RCB	1611	3 - 12x10 RCB	3 - 12x10 RCB	3 - 12x10 RCB
Railroad Track (N - 1, 2,and 3)	6,700	5905	8 - 12x12 RCB	270-FT ROW	33-FT DIA	4705	6 - 12x12 RCB	240-FT ROW	30-FT DIA
R2	3,100	534	2 - 10x8 RCB	2 - 10x8 RCB	13-FT DIA	534	2 - 10x8 RCB	2 - 10x8 RCB	13-FT DIA
R1	300	763	2 - 10x10 RCB	2 - 10x10 RCB	13-FT DIA	763	2 - 10x10 RCB	2 - 10x10 RCB	13-FT DIA
I610-2	3,250	1037	2 - 10x8 RCB	2 - 10x8 RCB	18-FT DIA	1037	2 - 10x8 RCB	2 - 10x8 RCB	18-FT DIA
E-1	1,800	282	1 - 12x9 RCB	1 - 12x9 RCB	1 - 12x9 RCB	282	1 - 12x9 RCB	1 - 12x9 RCB	1 - 12x9 RCB
F-1	1,800	462	2 - 12x9 RCB	2 - 12x9 RCB	2 - 12x9 RCB	462	2 - 12x9 RCB	2 - 12x9 RCB	2 - 12x9 RCB
Cost Estimate			**$635,000,000**	**$777,000,000**	**$681,000,000**		**$558,000,000**	**$722,000,000**	**$633,000,000**

TABLE 7

Concept B - I610 Tunnel Alignment

Element	Length (feet)	Q (cfs)	10-YR With Chimney Rock Overflow		Q (cfs)	10-YR Without Chimney Rock Overflow	
			Storm Sewer	Tunnel		Storm Sewer	Tunnel
N-4	3,200	803	2-11x10 RCB	16 ft DIA	803	2-11x10 RCB	16 ft DIA
I610-4	4,100	2024	5-12x12 RCB	28 ft DIA	1390	4-12x12 RCB	24 ft DIA
I610-3	2,660	2556	5-12x12 RCn	28 ft DIA	1805	4-12x12 RCn	24 ft DIA
I610-2	3,200	2776	6-12x12 RCB	27 ft DIA	1966	5-12x12 RCB	23 ft DIA
I610-1	2,920	3070	6-12x12 RCB	32 Ft DIA	2186	5-12x12 RCB	27 ft DIA
R-4	2,580	715	3-9x7 RCB	12 ft dia	415	2-9x6 RCB	10 ft dia
R-3	2,730	675	2-10x9 RCB	13 ft dia	375	1-10x9 RCB	10 ft dia
R-2	2,730	260	1-10x7 RCB	8 ft dia	260	1-10x7 RCB	8 ft dia
R-1 (F-1 and E-1)	4,236	392	2-10x10 RCB	-	392	2-10x10 RCB	-
N-3	3,700	321	2-10x8 RCB	10 ft dia	321	2-10x8 RCB	10 ft dia
N-2	2,700	493	4-10c10 RCB	16 ft dia	493	4-10c10 RCB	16 ft dia
N-1	300	715	4-10x10 RCB	-	715	4-10x10 RCB	-
Cost Estimate			**$530,000,000**	**$603,000,000**		**$461,000,000**	**$531,000,000**

Element	Length (feet)	Q (cfs)	100-YR With Chimney Rock Overflow		Q (cfs)	100-YR Without Cypress Overflow	
			Storm Sewer	Tunnel		Storm Sewer	Tunnel
N-4	3,200	1611	4-11x10 RCB	21 ft DIA	1611	4-11x10 RCB	21 ft DIA
I610-4	4,100	4081	11-12x12 RCB	38 ft DIA	2858	8-12x12 RCB	32 ft DIA
I610-3	2,660	5023	11-12x12 RCB	38 ft DIA	3774	8-12x12 RCB	33 ft DIA
I610-2	3,200	5378	11-12x12 RCB	35 ft DIA	4145	10-12x12 RCB	32 ft DIA
I610-1	2,920	5963	11-12x12 RCB	43 ft DIA	4652	10-12x12 RCN	38 ft DIA
R-4	2,580	1438	3-10x10 RCB	16 ft dia	837	2-10x10 RCB	13 ft dia
R-3	2,730	1375	4-10x9 RCB	17 ft dia	775	2-10x9 RCB	13 ft dia
R-2	2,730	534	2-10x7 RCB	11 ft dia	534	2-10x7 RCB	11 ft dia
R-1 (F-1 and E-1)	4,236	813	3-12x12 RCB	-	813	3-12x12 RCB	-
N-3	3,700	663	2-10x10 RCB	13 ft dia	663	2-10x10 RCB	13 ft dia
N-2	2,700	1032	3-12x12 RCB	22 ft dia	1032	3-12x12 RCB	22 ft dia
N-1	300	1500	3-12x12 RCB	22 ft dia	1500	3-12x12 RCB	22 ft dia
Cost Estimate			**$900,000,000**	**$783,000,000**		**$764,000,000**	**$703,000,000**

TABLE 7
Concept C - Existing Drainage System Routes

			10-YR With Chimney Rock Overflow	
Element	**Length (feet)**	**Q (cfs)**	**Storm Sewer**	**Tunnel**
R-4	4,048	714.9	3-10x10 RCB	16 ft dia
R-3	2,800	1283.3	4-10x10 RCB	23 ft dia
R-2	3,200	1409.2	5-10x10 RCB	20 ft dia
R-1	300	1539.4	5-10x10 RCB	21 ft dia
I610-4	4,011	562.0	2-12x10 RCB	16 ft dia
I610-3	2,656	838.8	2-12x10 RCB	18 ft dia
I610-2	3,157	921.0	2-12x10 RCB	17 ft dia
I610-1	300	1133.7	2-12x10 RCB	18 ft dia
N-4	5,300	803.0	3-12x10 RCB	14 ft dia
N-3	2,656	871.2	3-12x10 RCB	14 ft dia
N-2	3,157	912.5	4-12x10 RCB	21 ft dia
N-1	300	1125.7	4-12x10 RCB	24 ft dia
	Cost Estimate		**$442,000,000**	**$524,000,000**

	10-YR Without Chimney Rock Overflow	
Q (cfs)	**Storm Sewer**	**Tunnel**
414.9	2 - 10x10 RCB	13 ft dia
683.3	3-10x10 RCB	18 ft dia
809.2	4-10x10 RCB	16 ft dia
939.4	4-10x10 RCB	17 fr dia
562.0	2-12x10 RCB	16 ft dia
838.8	2-12x10 RCB	18 ft dia
921.0	2-12x10 RCB	17 ft dia
1133.7	2-12x10 RCB	18 ft dia
803.0	3-12x10 RCB	14 ft dia
871.2	3-12x10 RCB	14 ft dia
912.5	4-12x10 RCB	21 ft dia
1125.7	4-12x10 RCB	24 ft dia
	$405,000,000	**$500,000,000**

			100-YR With Chimney Rock Overflow	
Element	**Length (feet)**	**Q (cfs)**	**Storm Sewer**	**Tunnel**
R-4	4,048	1437.8	5-10x10 RCB	21 ft dia
R-3	2,800	2612.6	8-10x10 RCB	31 ft dia
R-2	3,200	2890.0	8-10x10 RCB	27 ft dia
R-1	300	3162.6	8-10x10 RCB	28 ft dia
I610-4	4,011	1138.7	4-12x10 RCB	22 ft dia
I610-3	2,656	1738.2	4-12x10 RCB	24 ft dia
I610-2	3,157	1926.8	4-12x10 RCB	23 ft dia
I610-1	300	2373.0	4-12x10 RCB	25 ft dia
N-4	5,300	1611.1	6-12x10 RCB	19 ft dia
N-3	2,656	1801.4	8-12x10 RCB	19 ft dia
N-2	3,157	1918.5	8-12x10 RCB	29 ft dia
N-1	300	2368.5	8-12x10 RCB	33 ft dia
	Cost Estimate		**$801,000,000**	**$757,000,000**

	100-YR Without Cypress Overflow	
Q (cfs)	**Storm Sewer**	**Tunnel**
837.8	3-10x10 RCB	17 ft dia
1412.6	5-10x10 RCB	24 ft dia
1690.0	6-10x10 RCB	21 ft dia
1962.6	6-10x10 RCB	23 ft dia
1138.7	4-12x10 RCB	22 ft dia
1738.2	4-12x10 RCB	24 ft dia
1926.8	4-12x10 RCB	23 ft dia
2373.0	4-12x10 RCB	25 ft dia
1611.1	6-12x10 RCB	19 ft dia
1801.4	8-12x10 RCB	19 ft dia
1918.5	8-12x10 RCB	29 ft dia
2368.5	8-12x10 RCB	33 ft dia
	$717,000,000	**$687,000,000**

Innovative approaches
Practical results
Outstanding service

10497 Town and Country Way, Suite 500 + Houston, Texas 77024 + 713-600-6800 + FAX 817-735-7491 www.freese.com

TO: James Andrews, P.E., ARKK

CC: J. Stephen Wilcox, P.E., CFM, Costello

FROM: Brian Gettinger, P.E.

SUBJECT: Conceptual Tunnel Constructability and Cost Analysis

DATE: 7/27/2020

PROJECT: City of Bellaire Master Drainage Concept Plan

DRAFT
THIS DOCUMENT IS RELEASED FOR THE PURPOSE OF INTERIM REVIEW UNDER THE AUTHORITY OF **BRIAN GETTINGER**, P.E., TEXAS NO. **128472** ON **July 27, 2020**. IT IS NOT TO BE USED FOR CONSTRUCTION, BIDDING OR PERMIT PURPOSES. FREESE AND NICHOLS, INC. TEXAS REGISTERED ENGINEERING FIRM F-2144

1.0 PURPOSE

The purpose of this memo is to provide supporting analysis related to tunnels for the Concept Plan Memorandum prepared by Costello Engineering & Surveying for the City of Bellaire Master Drainage Concept Plan.

2.0 TUNNEL METHODS OF CONSTRUCTION

The anticipated method of construction for tunnels considered as part of this analysis is based on the diameter and length of the tunnel.

For tunnels greater than 12 feet in diameter, a pressurized face tunnel boring machine (likely an earth pressure balance (EPB) tunnel boring machine (TBM)) installing precast concrete segment lining is assumed. Detailed information on this method of construction is provided in the "Preliminary Opinion of Tunneling Applicability Memorandum" prepared as part of the Harris County Flood Control District Phase 1 Tunnel Study completed in 2019.

Key planning considerations are based on the results of "Preliminary Opinion of Tunneling Applicability Memorandum." Specific considerations applicable to this analysis of a pressurized face tunnel boring machine installing precast concrete segments as final liner include:

- Tunnel curve radius shall be 1,000 feet or greater.
- Tunnel depth is assumed to be approximately 100 feet to avoid deep foundations and other utilities and minimize impact to surface structures.

- Maximum distance between construction shafts shall be 5 miles.
- Finished tunnel diameters between 90 inches and 50 feet are constructible.
- Right of way (ROW) width for the tunnel should be two times (2x) the tunnel diameter.
- Tunnel Launch Shaft Area shall be greater than or equal to 5 acres.
- Tunnel Retrieval Shaft Area shall be greater than or equal to 1 acre.
- Flow Drop Shafts shall be greater than or equal to 0.5 acre.
- Access Shafts for inspection and maintenance should be provided every 6,000 ft. Access shafts can be combined with flow drop shafts.
- Flow drops and Access Shafts shall be located directly above or near the tunnel (due to the soil conditions, construction of long adits can be challenging).
- The excavated diameter cannot be changed without using a different machine, requiring a different launch shaft site along the alignment.

Figure 1 – Precast Concrete Segment Lined Tunnel under Construction (Northeast Boundary Tunnel, Washington DC)

For tunnels less than or equal to 12 feet in diameter and less than 5,000 feet long, a pressurized face microtunnel boring machine (MTBM) jacking concrete pipe is assumed. Microtunneling requires a much smaller footprint for shafts, but the distance between shafts is much less than for a TBM. Microtunneling planning considerations:

- Straight alignments, no curve radii
- Maximum distance between shafts should be limited to 2000 feet (assuming Interjack station usage and diameter > 8 feet)
- Right of way (ROW) width for the tunnel preferred to be two times (2x) the tunnel diameter.
- Microtunnel Launch Shaft are shall be greater than or equal to 0.5 acres.
- Microtunnel Retrieval Shaft Area can be small and is generally limited to a shaft 1.5x the diameter of the microtunnel and small surrounding area.
- Flow drop and access shafts are not required between construction shafts.
- The excavated diameter cannot be changed without using a different machine, requiring a different launch shaft site along the alignment.

Figure 2 – Microtunnel Road Crossing (Sabine River Authority)

3.0 TUNNEL HYDRAULIC CAPACITY

For all concepts, the system sizing presented is based on hydraulic capacity as calculated by the methodology presented in in the "Inverted Siphon Hydraulic Analysis Memorandum" prepared as part of the Harris County Flood Control District Phase 1 Tunnel Study completed in 2019.

The tunnel would flow as pressure flow, relying on differential hydraulic head between a higher elevation (generally north and west in Bellaire) and a lower elevation at the outfall (Cypress Slough or Brays Bayou). The tunnel diameters presented were determined based on the tunnel length, differential MPE (maximum ponding elevation) between nodes and assumptions on surface roughness consistent with the HCFCD analysis. For equal tunnel lengths, the greater the differential water surface elevation the greater the conveyance capacity in the tunnel. The tunnel system is intended to operate entirely by gravity with dewatering pumps provided only to drain the tunnel in between storm events. Capacity augmentation could be provided by pumping at the downstream end, but due to concerns about system operations and maintenance this is not recommended at this time.

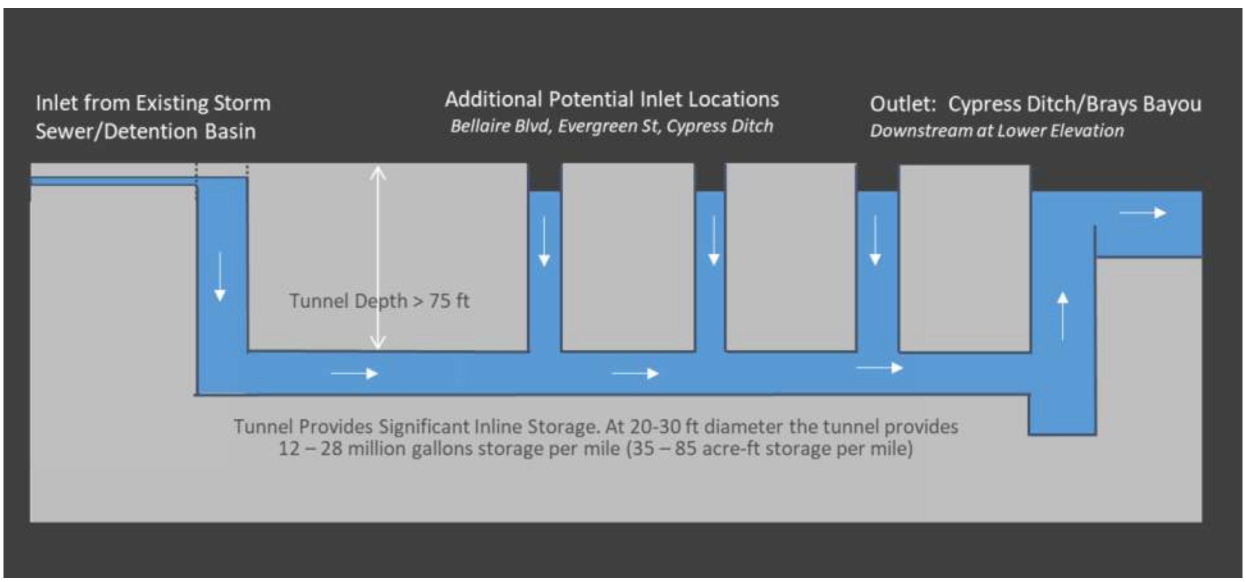


Figure 3 – Inverted Siphon Tunnel Concept

4.0 PRELIMINARY CONSTRUCTABILITY ANALYSIS OF CONCEPTS

This section identifies preliminary constructability input of the hydraulic routing concepts. In all instances the diameters presented by the hydraulic analysis need to be revised to provide consistency between segments to minimize the need to change diameters between nodes requiring different equipment and significant additional mobilization costs.

4.1 CONCEPT A

Concept A originates on the east side of Bellaire, follows a northerly track to Bellaire Boulevard where it heads west, crosses under 610 and then heads north along Rice Boulevard to a point just south of Gulfton/Fournace.

This route has challenges with locating a suitable tunnel launch site near the confluence of Cypress Slough Ditch and Brays Bayou. A large site will be required to launch the large diameter tunnel boring machine necessary for hydraulic conveyance. There are no publicly owned properties 5 acres in size in that area. The City of Houston is considering consolidating the Southwest Wastewater Treatment Plant to Almeda Sims Wastewater Treatment Plant. If that project moves forward the Southwest WWTP site could be used as a launch shaft. Although the timeline of when this would be available is unclear and is dependent on the City of Houston’s project moving forward. It is unlikely that this site would be available for use as a tunnel launch shaft until late the late 2020s.

On the south side of Brays Bayou, the median of Braeswood Boulevard between Linkwood and the Railroad Tracks is approximately 3 acres. Although smaller than the preferred 5 acres, this site could be used with additional laydown and staging area nearby.

Concept A makes 90 degree turns at Bellaire Boulevard to the West and at Rice Boulevard to the North. The tunnel boring machine has a minimum 1,000-foot curve radius and cannot make a 90-degree turn. To make a sharp turn another launch shaft site would have to be located at the turn, based on a review of each of these intersections significant property acquisition would be required. The 1,000 ft curve radius could be used but would require the tunnel to cross outside of public right-of-way (ROW) and under private property, possibly under structures. This can be constructed but would require a subterranean easement to be obtained from the property owner. Although much less restrictive than a surface utility easement, private property owners still generally express reservations. Condemnation is possible but can be a lengthy process.

If minor collectors are to be tunneled, very limited space exists to launch machines, even for the smaller space requirements for a microtunnel with the exception of N-4 which could utilize a City of Bellaire property at the corner of Newcastle and Bellaire Blvd. Use of a microtunnel limits the maximum diameter to 12 feet which may not provide a large enough cross section to convey the modeled flow rate. Based on the limited space and additional easement acquisition, concept A is considered unfavorable compared to other options.

4.2 CONCEPT B

Concept B originates on the south side of Brays Bayou along IH-610 at an existing City of Houston owned detention basin. The tunnel could also originate on the north side of Brays Bayou at the Harris County Flood Control District owned former Meyer Grove Apartment complex. Both sites offer adequate space to launch a tunnel boring machine of the scale indicated by the hydraulic models.

This conceptual alignment is nearly entirely within ROW owned by the Texas Department of Transportation until it crosses Fournace Place. The conceptual alignment is beneath the southbound access road on the west side of IH-610. Use of this ROW will require approval by TXDOT.

There are not any locations for interim shaft sites along the route large enough to launch another tunnel boring machine without significant property acquisition and community impact; therefore at this time it is recommended that the tunnel maintain the same diameter for the entire alignment. The tunnel length is approximately 3.5 miles which is within the length that can be excavated from a single shaft. Following tunnel excavation if smaller diameters are needed at the upstream end to ensure minimum velocities for solids suspension, cast in place concrete lining could be installed within the precast concrete segments.

Further consideration should be given to a flow drop shaft at Cypress Ditch. Due to the low ground surface elevation at this point, flow may attempt to exit the tunnel instead of the outfall structure at Brays Bayou. Other mitigation measures are recommended for Cypress Ditch.

Flow drop structures into the tunnel are also planned at Evergreen Street, Bellaire Boulevard and Fournace Place along with potential minor collectors to the west to South Rice Avenue. These lateral connections (R2, R3 and R4) if constructed by tunnels could only be done by microtunnel due to space limitations and therefore could be no larger than 12 ft inside diameter (max pipe size). This is smaller than hydraulically preferred for some scenarios.

Property acquisition of home(s) will be required at Evergreen Street for a flow drop on the west side of the IH-610 access lanes on either the north or south of Evergreen. The soft corner in front of Frost Bank Building at Bellaire Blvd and IH-610 may offer enough space for a flow drop shaft structure. Additional investigation is needed into this site.

A 1,000 ft radius turn appears to be possible from IH-610 ROW onto Glenmont by crossing under Pin Oak Park in front of Pin Oak Middle School (subterranean easement required). No open property is available at Newcastle Road and Glenmont to remove the tunnel boring machine. It is recommended that the alignment be lengthened to the east and remove the TBM from the Centerpoint owned property east of Mulberry Lane and Glenmont.

The minor collector along Newcastle Road between Cypress Ditch and Bellaire Boulevard alignment would require the TBM to be launched from the same location as discussed for Concept A – either at the Southwest WWTP or within the median on the south side of Brays Bayou.

4.3 CONCEPT C

Concept C utilizes minor collectors along major north/south transportation corridors including S Rice Avenue, IH-610 and Newcastle.

The constructability of the IH-610 minor collector is consistent with the main tunnel alignment discussed in Concept B. The constructability of the Newcastle minor collector is consistent with the main tunnel alignment as discussed in Concept A.

The dense urbanization along S Rice Avenue would result in significant property acquisition to launch the tunnel boring machine, drop flow into the tunnel and to retrieve the tunnel boring machine. There is no available property at S. Rice and Cypress Ditch to launch a machine without significant property acquisition. Similarly, a flow drop at the tight intersection of S Rice and Evergreen surrounded by residential would require property acquisition. A flow drop may be possible in the median at Bellaire and S Rice but would likely require removal of many mature live oak trees. Tree removal of mature trees is generally strongly opposed by the public and is not recommended. An undeveloped lot on NE corner of S Rice and Fournace (owned by SLS WEST LOOP LP) could be a favorable TBM removal location and flow drop location.

Based on the very limited property available along S Rice Avenue, Concept C is deemed unfavorable for tunnel construction. Additionally, the alignment would require 3 mobilizations (one for each minor collector). A tunnel boring machine mobilization is a significant fixed cost (likely exceeding $10 million) for this size of a project and limiting the number of mobilizations will result in more favorable pricing.

5.0 CONCEPTUAL COST OPINION

Conceptual cost opinion for tunnels is based on the methodology presented in the "Conceptual Tunnel Cost Analysis" prepared as part of the Harris County Flood Control District Phase 1 Tunnel Study completed in 2019.

Consistent with the conclusions of the "Conceptual Tunnel Cost Analysis" the following unit prices per foot of tunnel per foot of diameter have been assumed:

- 25-foot Diameter: $789/LFT/FT ($19,725/FT)
- 40-foot Diameter: $725/LFT/FT ($29,000/FT)

These costs are inclusive of mobilization, excavation, tunnel lining and shaft construction for a pressurized face tunnel boring machine installing precast concrete segments and a 50% contingency appropriate for this level of project development. For tunnel diameters between these values, interpolation is appropriate. Similarly, for diameters slightly larger or smaller than these, extrapolation is appropriate.

Where microtunnels are required due to site constraints or smaller diameters and shorter lengths a cost of $700 per foot of diameter per foot of tunnel has been assumed. This cost is inclusive of mobilization, shaft excavation, and tunnel pipe. These costs are deemed to have an appropriate level of conservativeness based on the early level of concept development and will be refined in future phases as more details are developed.

5.1 AACE COST ESTIMATE CLASSIFICATION

The concept-level cost estimate prepared for and summarized in this report was developed following the *Cost Estimate Classification System* developed by AACE (AACE, 2019). The *Cost Estimate Classification System* provides an approximate representation of the relationship of specific design input data and design deliverable maturity to the cost estimate accuracy and methodology used to produce the cost estimate. The AACE Cost Estimate Classification System (AACE 2019) is summarized in Table 1.

Table 1: AACE Cost Estimate Classification Matrix (AACE, 2019)

Estimate Class	Maturity Level[1]	Typical Estimate Purpose	Typical Estimating Method	Expected Accuracy Range[2]
Class 5	0% to 2%	Concept screening	SF factoring, parametric models, judgement, or analogy	L: -20% to -30% H: +30% to +50%
Class 4	1% to 15%	Schematic design or concept study	Parametric models, assembly driven models	L: -10% to -20% H: +20% to +30%
Class 3	10% to 40%	Design development, budget authorizing, feasibility	Semi-detailed unit costs with assembly level line items	L: -5% to -15% H: +10% to +20%
Class 2	30% to 75%	Control or bid/tender, semi-detailed	Detailed unit cost with forced detailed take-off	L: -5% to -10% H: +5% to +15%
Class 1	65% to 100%	Check estimate or pre-bid/tender, change order	Detailed unit cost with detailed take-off	L: -3% to -5% H: +3% to +10%

Notes:
1 – Maturity level of project definition deliverables expressed as percentage of complete definition
2 – The +/- value represents typical percentage of actual costs from the cost estimate after applying a contingency (typically at a 50% level of confidence) for given scope.

The estimated accuracy range for the cost estimate provided in Table 1 is plotted in Figure 4.

Since this project is at the conceptual phase with a maturity level of project definition deliverables close to 0%, the cost estimate provided herein is considered AACE Class 5. For the Class 5 cost estimate presented herein, the estimating methods used were unit cost factoring and judgement. For a Class 5 estimate, the estimated accuracy range after applying the contingency is:

- Low Range: -20% to -30%
- High Range: +30% to +50%

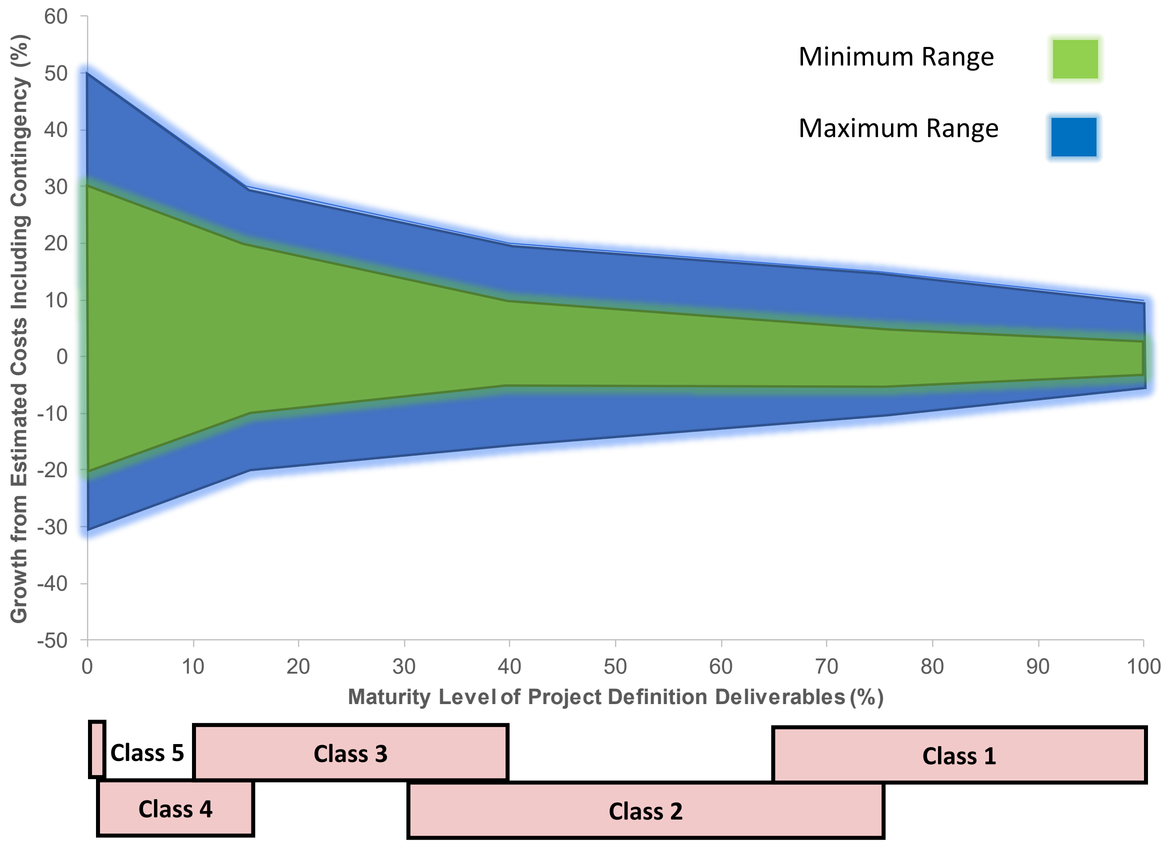


Figure 4: AACE Estimated Accuracy Range (AACE, 2019)

5.2 CONCEPT A COST OPINION

The cost opinion for Concept A has been developed assuming a large diameter major collector tunnel excavated by an earth pressure balance tunnel boring machine and minor collectors excavated by microtunnel. The minor collector maximum size is limited to 12 ft. In some segments this does not provide enough conveyance capacity to fully convey the maximum flow. In future phases parallel microtunnels should be investigated. The major collector tunnel originates on the south side of Brays Bayou and follows a northerly track to Bellaire Boulevard where it heads west, crosses under 610 and then heads north along Rice Boulevard to a point just south of Gulfton/Fournace. All changes of direction require a 1,000 ft radius turn and will require subterranean easement acquisition from private property owners.

Concept A Summary	Length (ft)	Major Collector DIA (ft)	Minor Collector DIA (ft)	Cost w/ 50% Contingency ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
10 Yr w/ Overflow	32,220	25	10 to 12	$452	$317	$678
10 Yr w/o Overflow	32,220	22	10 to 12	$412	$289	$619
100 Yr w/ Overflow	32,220	33	12	$562	$394	$844
100 Yr w/o Overflow	32,220	30	12	$523	$366	$784

5.3 CONCEPT B COST OPINION

The cost opinion for Concept B has been developed assuming a large diameter major collector tunnel excavated by an earth pressure balance tunnel boring machine and minor collectors excavated by microtunnel. The minor collector maximum size is limited to 12 ft. In some segments this does not provide enough conveyance capacity to fully convey the maximum flow. In future phases parallel microtunnels should be investigated. The major collector tunnel is assumed to begin at the former Meyer Grove apartments north of Brays Bayou and terminate at the Centerpoint property east of Mulberry Lane and Glenmont Drive.

Concept B Summary	Length (ft)	Major Collector DIA (ft)	Minor Collector DIA (ft)	Cost w/ 50% Contingency ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
10 Yr w/ Overflow	30,650	28	8 to 12	$477	$334	$716
10 Yr w/o Overflow	30,650	24	8 to 12	$417	$417	$292
100 Yr w/ Overflow	30,650	38	11 to 12	$616	$616	$431
100 Yr w/o Overflow	30,650	33	11 to 12	$549	$549	$384

5.4 CONCEPT C COST OPINION

The cost opinion for Concept C has been developed assuming a large diameter minor collector tunnel excavated by an earth pressure balance tunnel boring machine along Interstate 610 and Newcastle. A cost opinion for the minor collector along S. Rice was not prepared as this alignment was not deemed constructible due to lack of available construction shaft sites. The cost opinion only includes cost for the Interstate 610 and Newcastle minor collectors.

Concept C Summary	Length (ft)	Major Collector DIA (ft)	Minor Collector DIA (ft)	Cost w/ 50% Contingency ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
10 Yr w/ Overflow	21,550	-	18 to 21	$295	$207	$443
10 Yr w/o Overflow	21,550	-	18 to 21	$295	$207	$443
100 Yr w/ Overflow	21,550	-	24 to 29	$402	$281	$603
100 Yr w/o Overflow	21,550	-	24 to 29	$402	$281	$603

6.0 SUMMARY

Although the City of Bellaire is highly urbanized limiting the availability of potential launch sites and limiting routing options within publicly owned right of way, tunnel alternatives to convey significant stormwater flows by gravity in an inverted siphon tunnel are constructible and present a significantly lower community and public impact than trenched box culvert or open ditch improvements. Initial analysis elevates Concept B as the most feasible and least impactful to the community assuming that use of TXDOT ROW can be used. Concept A is also constructible but will require a greater number of subterranean easements at the transition between North/South and East/West public ROW. Concept C is not recommended for tunneling due to challenges along S Rice Avenue.

Further analysis into shaft site locations and initial discussions with property owners include TXDOT are recommended to further advance this concept.

7.0 REFERENCES

Association for the Advancement of Cost Estimating (AACE) International

- AACE International, 2019, Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Building and General Construction Industries, TCM Framework: 7.3 – Cost Estimating and Budgeting, Recommended Practice No. 56R-08.

Harris County Flood Control District

- Tunnel Study Phase One, 2019
    - Preliminary Opinion of Tunneling Applicability Memorandum
    - Inverted Siphon Hydraulic Analysis Memorandum
    - Conceptual Tunnel Cost Analysis

8.0 APPEDNIX – COST DETAIL

Tunnel Concept A 10 YR Conceptual Cost Opinion w/ overflow

Major Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Main Route	N-1, N-2, N-3, I610-3, R-3, R-4	17,250	25	$331	$232	$496

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Rice	R2	3,100	10	$22	$15	$33
Rice	R1	300	12	$3	$2	$4
Fournace Pl	I610-2	3,250	12	$27	$19	$41
610 N of Bellaire Blvd	I610-4	3,420	12	$29	$20	$43
Newcastle N of Bellaire Blvd	N4	4,900	12	$41	$29	$62
	Concept B Total	**32,220**	-	**$452**	**$317**	**$678**

Tunnel Concept A 10 YR Conceptual Cost Opinion w/o overflow

Major Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Main Route	N-1, N-2, N-3, I610-3, R-3, R-4	17,250	22	$291	$204	$437

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Rice	R2	3,100	10	$22	$15	$33
Rice	R1	300	12	$3	$2	$4
Fournace Pl	I610-2	3,250	12	$27	$19	$41
610 N of Bellaire Blvd	I610-4	3,420	12	$29	$20	$43
Newcastle N of Bellaire Blvd	N4	4,900	12	$41	$29	$62
	Concept B Total	**32,220**	-	**$412**	**$289**	**$619**

Tunnel Concept A 100 YR Conceptual Cost Opinion w/ overflow

Major Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Main Route	N-1, N-2, N-3, I610-3, R-3, R-4	17,250	33	$437	$306	$655

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Rice	R2	3,100	12	$26	$18	$39
Rice	R1	300	12	$3	$2	$4
Fournace Pl	I610-2	3,250	12	$27	$19	$41
610 N of Bellaire Blvd	I610-4	3,420	12	$29	$20	$43
Newcastle N of Bellaire Blvd	N4	4,900	12	$41	$29	$62
	Concept B Total	**32,220**	-	**$562**	**$394**	**$844**

Tunnel Concept A 100 YR Conceptual Cost Opinion w/o overflow

Major Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Main Route	N-1, N-2, N-3, I610-3, R-3, R-4	17,250	30	$397	$278	$595

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Rice	R2	3,100	12	$26	$18	$39
Rice	R1	300	12	$3	$2	$4
Fournace Pl	I610-2	3,250	12	$27	$19	$41
610 N of Bellaire Blvd	I610-4	3,420	12	$29	$20	$43
Newcastle N of Bellaire Blvd	N4	4,900	12	$41	$29	$62
	Concept B Total	**32,220**	-	**$523**	**$366**	**$784**

Diameter limited by construction method and less than necessary to fully convey flow

Tunnel Concept B 10 YR Conceptual Cost Opinion w/ overflow

Major Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
IH-610 Route	I610-1, I610-2, I610-3, I610-4, N-4	17,350	28	$373	$261	$559

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Evergreen St	R-2	2,600	8	$15	$10	$22
Bellaire Blvd	R-3	2,500	12	$21	$15	$32
Fournace Pl	R-4	2,400	12	$20	$14	$30
Newcastle	N-2, N-3	5,800	12	$49	$34	$73
	10 Yr w/ Overflow	**30,650**	-	**$477**	**$334**	**$716**

Tunnel Concept B 10 YR Conceptual Cost Opinion w/o overflow

Major Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Main Route	N-1, N-2, N-3, I610-3, R-3, R-4	17,350	24	$319	$224	$479

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Evergreen St	R-2	2,600	8	$15	$10	$22
Bellaire Blvd	R-3	2,500	10	$18	$12	$26
Fournace Pl	R-4	2,400	10	$17	$12	$25
Newcastle	N-2, N-3	5,800	12	$49	$34	$73
	10 Yr w/o Overflow	**30,650**	-	**$417**	**$292**	**$625**

Tunnel Concept B 100 YR Conceptual Cost Opinion w/ overflow

Major Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Main Route	N-1, N-2, N-3, I610-3, R-3, R-4	17,350	38	$506	$354	$759

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Evergreen St	R-2	2,600	11	$20	$14	$30
Bellaire Blvd	R-3	2,500	12	$21	$15	$32
Fournace Pl	R-4	2,400	12	$20	$14	$30
Newcastle	N-2, N-3	5,800	12	$49	$34	$73
	100 Yr w/ Overflow	**30,650**	-	**$616**	**$431**	**$923**

Tunnel Concept B 100 YR Conceptual Cost Opinion w/o overflow

Major Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Main Route	N-1, N-2, N-3, I610-3, R-3, R-4	17,350	33	$439	$307	$659

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Evergreen St	R-2	2,600	11	$20	$14	$30
Bellaire Blvd	R-3	2,500	12	$21	$15	$32
Fournace Pl	R-4	2,400	12	$20	$14	$30
Newcastle	N-2, N-3	5,800	12	$49	$34	$73
	100 Yr w/o Overflow	**30,650**	-	**$549**	**$384**	**$824**

Diameter limited by construction method and less than necessary to fully convey flow

Tunnel Concept C 10 YR Conceptual Cost Opinion w/ overflow

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Rice	R-2	10,350	-	-	-	-
610	R-3	10,150	18	$128	$90	$192
Newcastle	R-4	11,400	21	$168	$117	$251
	Concept C Total	**21,550**	-	**$295**	**$207**	**$443**

Tunnel Concept C 10 YR Conceptual Cost Opinion w/o overflow

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Rice	R-2	10,350	-	-	-	-
610	R-3	10,150	18	$128	$90	$192
Newcastle	R-4	11,400	21	$168	$117	$251
	Concept C Total	**21,550**	-	**$295**	**$207**	**$443**

Tunnel Concept C 100 YR Conceptual Cost Opinion w/ overflow

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Rice	R-2	10,350	-	-	-	-
610	R-3	10,150	24	$171	$119	$256
Newcastle	R-4	11,400	29	$231	$162	$347
	Concept C Total	**21,550**	-	**$402**	**$281**	**$603**

Tunnel Concept C 100 YR Conceptual Cost Opinion w/o overflow

Minor Collector	Label	Length (ft)	Diameter (ft)	Cost ($M)	AACE Low $M (-30%)	AACE High $M (+50%)
Rice	R-2	10,350	-	-	-	-
610	R-3	10,150	24	$171	$119	$256
Newcastle	R-4	11,400	29	$231	$162	$347
	Concept C Total	**21,550**	-	**$402**	**$281**	**$603**

Not constructible with tunneling methods