TECHNICAL SUPPORT DOCUMENT: BACTERIA TOTAL MAXIMUM DAILY LOADS FOR THE ARMAND BAYOU WATERSHED, HOUSTON, TEXAS (1113_02, 1113A_01, 1113B_01, 1113C_01, 1113D_01 AND 1113E_01)

(photo courtesy of Armand Bayou Nature Center)

http://www.abnc.org/index.php?mact=PicasaWebAlbumBrowser,cntnt01,default,0&cntnt01user=armandbayou%40gmail.com&cntnt01albumid=5342408988796246913&cntnt01imagethumbsize=144&cntnt01albumthumbsize=&cntnt01imagesize=720&cntnt01include=ABNC&cntnt01exclude=&cntnt01returnid=24

Prepared for:

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

Prepared by:

University of Houston

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ACRONYMS AND ABBREVIATIONS

ASAE	American Society of Agricultural Engineers
C-CAP	Coastal Change Analysis Program
CAFO	concentrated animal feeding operation
CFR	Code of Federal Regulations
cfs	cubic feet per second
counts	colony forming unit
CN	curve number
dL	deciliter
DMR	discharge monitoring report
E coli	Escherichia coli
FDC	flow duration curve
GCHD	Galveston County Health District
GIS	geographic information system
HCFCD	Harris County Flood Control District
HCOEM	Harris County Office of Emergency Management
H-GAC	Houston-Galveston Area Council
LA	load allocation
LDC	load duration curve
mL	milliliter
MOS	margin of safety
MS4	municipal separate storm sewer system
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
NRCS	National Resources Conservation Service
OSSF	on-site sewage facility
RMSE	root mean square error
SSO	sanitary sewer overflow
SWQS	surface water quality standards
SWQMIS	Surface Water Quality Monitoring Information System
TAC	Texas Administrative Code
TCEQ	Texas Commission on Environmental Quality
TCOON	Texas Coastal Ocean Observation Network
TMDL	Total Maximum Daily Loads
TPDES	Texas Pollution Discharge Elimination System
TSARP	Tropical Storm Allison Recovery Project
TWDB	Texas Water Development Board

USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WLA	waste load allocation
WQM	water quality monitoring
WQS	water quality standard
WWTF	wastewater treatment facility

CHAPTER 1
INTRODUCTION

1.1 Watershed Description

The Armand Bayou Watershed encompasses approximately 60 square miles of land located just southeast of the City of Houston, Texas and lies entirely within Harris County. The Armand Bayou Watershed is part of the San Jacinto-Brazos Coastal Basin, which covers the coastal portions of Galveston, Harris and Brazoria counties located between the San Jacinto River and the Brazos River. Armand Bayou is one of the major tributaries within this basin along with Clear Creek, Dickinson Bayou, Chocolate Bayou, Bastrop Bayou and Oyster Creek. Armand Bayou flows into Clear Lake (Segment 2425) which, in turn, feeds into Upper Galveston Bay (Segment 2421) which eventually discharges to the Gulf of Mexico (Segment 2501).

Armand Bayou lies wholly within the Northern Humid Gulf Coastal Prairies ecoregion, characterized by original vegetation consisting of "grasslands with a few clusters of oaks, known as oak mottes or maritime woodlands." As noted by Griffith et al. (2007), "almost all of the coastal prairies have been converted to cropland, rangeland, pasture or urban land uses" and the Armand Bayou watershed is no different: the northern and southwestern portions of the watershed are heavily developed while the lower and middle regions are sparsely developed. Within the lower region of the watershed, Armand Bayou Nature Center owns and manages 2500 acres as part of a wildlife and nature preserve. The watershed is expected to continue to develop based on its proximity to the Johnson Space Center, Houston Ship Channel, and Clear Lake.

Armand Bayou and its tributaries have both freshwater segments and tidally influenced mixed segments. The Texas Commission on Environmental Quality (TCEQ) classifies Armand Bayou as two separate waterbodies:

- Armand Bayou Tidal, Segment 1113 and
- Armand Bayou Above Tidal, Segment 1113A.

In addition, there are several tributaries to Armand Bayou that are unclassified but have been assigned assessment unit identification numbers by the TCEQ. Horsepen Bayou Tidal (1113B_01), Unnamed Tributary to Horsepen Bayou (1113C_01), and Big Island Slough (1113E_01) are tributaries to Armand Bayou Tidal. Willow Springs Bayou (1113D_01) is a tributary to Armand Bayou Above Tidal and is a freshwater stream.

Subwatershed List

This report focuses on the following waterbodies that TCEQ placed in Category 5 [303(d) list] of the Draft 2012 Integrated Report for nonsupport of contact recreation use:

- Armand Bayou Tidal (1113_02)
- Armand Bayou Above Tidal (1113A_01)
- Horsepen Bayou Tidal (1113B_01)
- Unnamed Tributary to Horsepen Bayou (1113C_01)

- Willow Springs Bayou (1113D_01)
- Big Island Slough (1113E_01)

Figure 1-1 is a location map showing these Texas waterbodies and their contributing watersheds. The delineation of each subwatershed is derived from 2005 geographic information system (GIS) data files created for the Tropical Storm Allison Recovery Project (TSARP) provided by Harris County Flood Control District (HCFCD). These waterbodies and their surrounding watersheds are hereinafter referred to as the Study Area.

The climate of the region is subtropical humid, with very hot and humid summers and mild winters. The average maximum daytime temperature is 34 degrees Celsius (93 degrees Fahrenheit) while the temperature averages between 4 and 16 degrees Celsius (39 to 61 degrees Fahrenheit) during the winter. Summer rainfall is dominated by sub-tropical convection, winter rainfall by frontal storms, and fall and spring months by combinations of these two (Burian 2005).

Table 1-1, derived from the 2000 and 2010 U.S. Census, demonstrates that the county in which the watershed is located is very densely populated. Table 1-1 also shows population growth for Harris County (U.S. Census Bureau 2010).

Table 1-1: County Population and Density

County Name	2000 U.S. Census	2000 Population Density (per square mile)	2010 U.S. Census	2010 Population Density (per square mile)
Harris	3,400,578	1,967	4,092,459	2,367

Source: U.S. Census 2000 and 2010

The six largest cities within Armand Bayou Watershed are expected to increase in population by an average of 16 percent from 2010 to 2030, according to the Texas Water Development Board (TWDB) (TWDB 2013). Table 1-2 lists TWDB population growth estimates for these six cities from 2010 to 2030. City of Houston is the largest City in the watershed and is anticipated to grow by 16% while Taylor Lake Village is the smallest city and is anticipated to grow a small amount, just 2% between 2010 and 2030.

Table 1-2: Armand Bayou Watershed Population Increases by City, 2010 to 2030

City	2010 Census Population	2020 Population Estimate	2030 Population Estimate	Growth Rate (2010-2030)
Deer Park	32,010	34,255	35,974	12%
Houston	2,058,056	2,201,986	2,377,662	16%
La Porte	33,800	34,345	34,774	3%
Pasadena	149,043	154,441	158,841	7%
Taylor Lake Village*	3,544	3,557	3,618	2%
Webster	10,400	15,071	16,187	56%

Source: Region H - Draft Population and Municipal Demand Projections for 2016 Regional and 2017 State Water Plan
http://www.twdb.state.tx.us/waterplanning/data/projections/2017/demandproj.asp

Population estimates for each Assessment Unit drainage area were derived from the 2010 Census and are provided in Table 1-3.

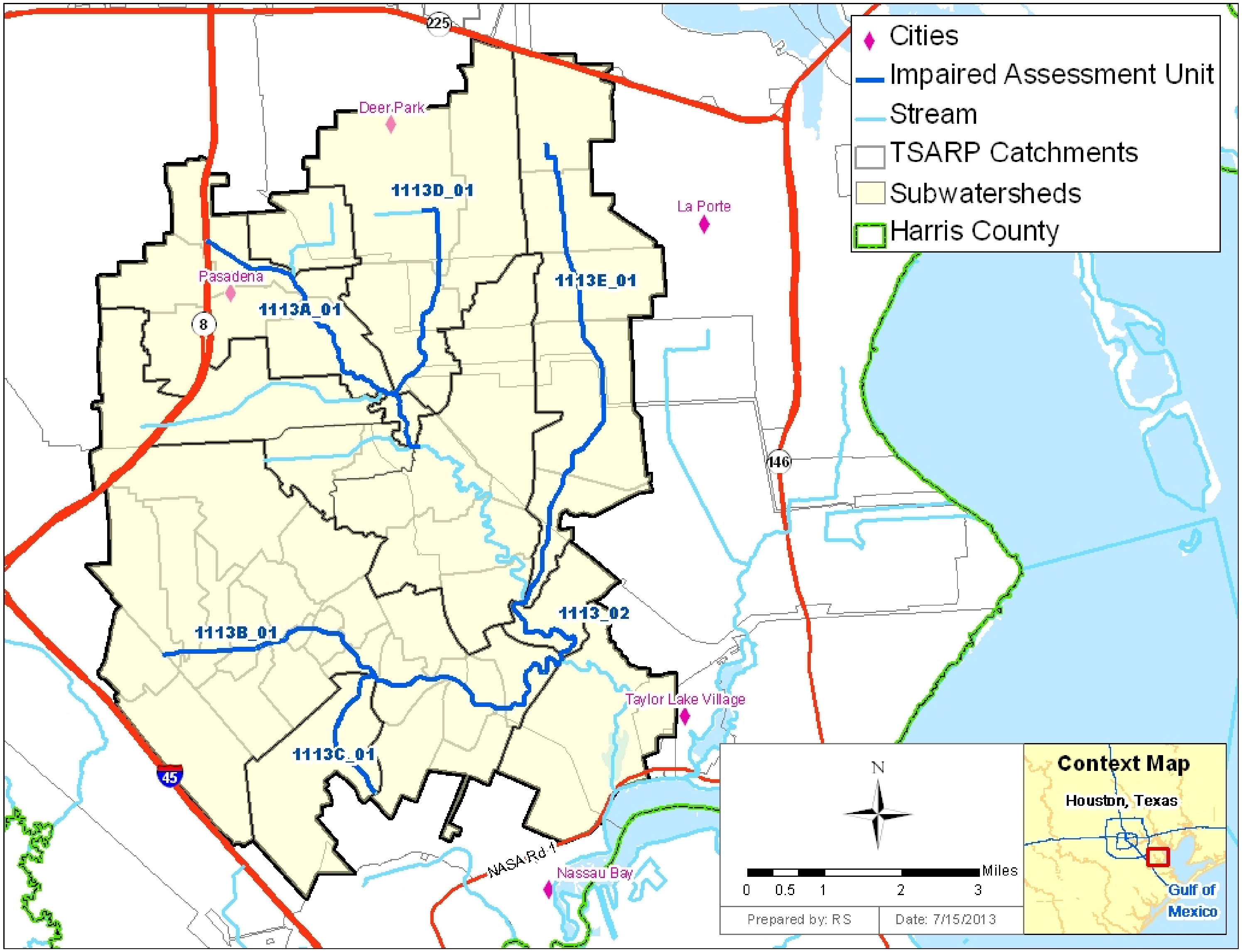

Figure 1-1: Location Map for Armand Bayou Watershed

Table 1-3: Population estimate by Assessment Unit

Segment Name	Assessment Unit	2010 Census Population Estimate	2010 Census Household Count
Armand Bayou Tidal	1113_02	294	207
Armand Bayou Above Tidal	1113A_01	14,376	5,277
Horsepen Bayou Tidal	1113B_01	27,494	11,076
Unnamed Tributary to Horsepen Bayou	1113C_01	17,680	8,041
Willow Springs Bayou	1113D_01	21,921	8,163
Big Island Slough	1113E_01	14,782	5,177

1.2 Summary of Existing Data

The following subsections summarize existing data relevant to soil, land cover, and precipitation throughout the watershed as well as the chemical and physical characteristics of the waterbodies using ambient water quality, stream flow, tide, and conductivity data.

1.2.1 Soil

The geology of the Armand Bayou Watershed is comprised of moderately to very clayey soils which combined with the flat topography in the area, results in the large amount of natural wetlands in the area (Coastal Coordination Council, 2006). The soil has a low water-bearing capacity, high moisture content, low permeability, and a high shrink-swell potential. The Soil Survey Geographic (SSURGO) Database National Resources Conservation Service (NRCS) 2012 information was used to characterize soil in the Study Area. As shown in Figure 1-2, the soil types that dominate the watershed are the Atasco, Beaumont, Bernard, and Gessner soil series. Table-1-3 lists the attributes of the soil series found in the Study Area; Table 1-4 provides the soil distribution in the Study Area.

Table 1-4: Characteristics of Soil Types of Armand Bayou Watershed

NRCS Soil Type	Surface Texture	Soil Series Name	Hydro-logic Soil Group	Soil Drainage Class	Average Available Water Storage (cm)
TX201	Loam	Addicks loam	B/D	Poorly Drained	30.0
TX201	Loam	Addicks-Urban land complex	B/D	Poorly Drained	30.0
TX201	Very Fine Sandy Loam	Aldine very fine sandy loam	D	Somewhat Poorly Drained	26.5
TX201	Very Fine Sandy Loam	Aldine-Urban land complex	D	Somewhat Poorly Drained	26.5
TX201	Fine Sandy Loam	Aris fine sandy loam	C	Poorly Drained	21.4
TX201	Fine Sandy Loam	Atasco fine sandy loam, 1 to 4 percent slopes	D	Moderately Well Drained	27.1
TX201	Clay	Beaumont clay	D	Poorly Drained	22.5
TX201	Clay Loam	Bernard clay loam	D	Somewhat Poorly Drained	24.9
TX201	Clay Loam	Bernard-Edna complex	D	Somewhat Poorly Drained	23.9
TX201	Clay Loam	Bernard-Urban land complex	D	Somewhat Poorly Drained	24.9
TX201	Loam	Gessner loam	B/D	Poorly Drained	25.0
TX201	Clay	Ijam soils	D	Poorly Drained	16.5
TX201	Clay	Lake Charles clay, 0 to 1 percent slopes	D	Moderately Well Drained	27.0
TX201	Clay	Lake Charles-Urban land complex	D	Moderately Well Drained	27.0
TX201	Silty Clay Loam	Verland silty clay loam	D	Somewhat Poorly Drained	27.2
TX201	Silty Clay Loam	Verland-Urban land complex	D	Somewhat Poorly Drained	27.2
TX201	Loam	Nahatche loam	B/D	Somewhat Poorly Drained	23.4
TX201	n/a	Urban land	D	n/a	0.0
TX201	Clay	Vamont clay, 0 to 1 percent slopes	D	Somewhat Poorly Drained	27.0
TX201	Clay	Vamont clay, 1 to 4 percent slopes	D	Somewhat Poorly Drained	27.0

All information derived from SSURGO data: http://datagateway.nrcs.usda.gov/
http://soils.usda.gov/survey/online_surveys/texas/harrisTX1976/harris.pdf

Table 1-5: Soil Type Distribution in Armand Bayou Watershed

	Assessment Unit					
Soil Series Name	**1113_02**	**1113A_01**	**1113B_01**	**1113C_01**	**1113D_01**	**1113E_01**
Addicks loam	0%	14%	6%	0%	3%	0%
Addicks-Urban land complex	0%	16%	2%	0%	4%	0%
Aldine very fine sandy loam	0%	0%	0%	0%	0%	0%
Aldine-Urban land complex	6%	0%	1%	0%	0%	0%
Aris fine sandy loam	21%	0%	1%	0%	0%	30%
Atasco fine sandy loam, 1 to 4 percent slopes	0%	20%	16%	25%	15%	0%
Beaumont clay	0%	0%	5%	1%	35%	27%
Bernard clay loam	0%	10%	8%	2%	11%	1%
Bernard-Edna complex	0%	0%	0%	10%	0%	0%
Bernard-Urban land complex	0%	34%	43%	27%	27%	22%
Gessner loam	0%	6%	15%	34%	0%	5%
Ijam soils	52%	0%	1%	0%	5%	1%
Lake Charles clay, 0 to 1 percent slopes	3%	0%	0%	0%	0%	0%
Lake Charles-Urban land complex	0%	0%	0%	0%	0%	0%
Verland silty clay loam	6%	0%	0%	0%	0%	11%
Verland-Urban land complex	4%	0%	2%	1%	0%	3%
Nahatche loam	8%	0%	0%	0%	0%	0%

All information derived from SSURGO data: http://datagateway.nrcs.usda.gov/

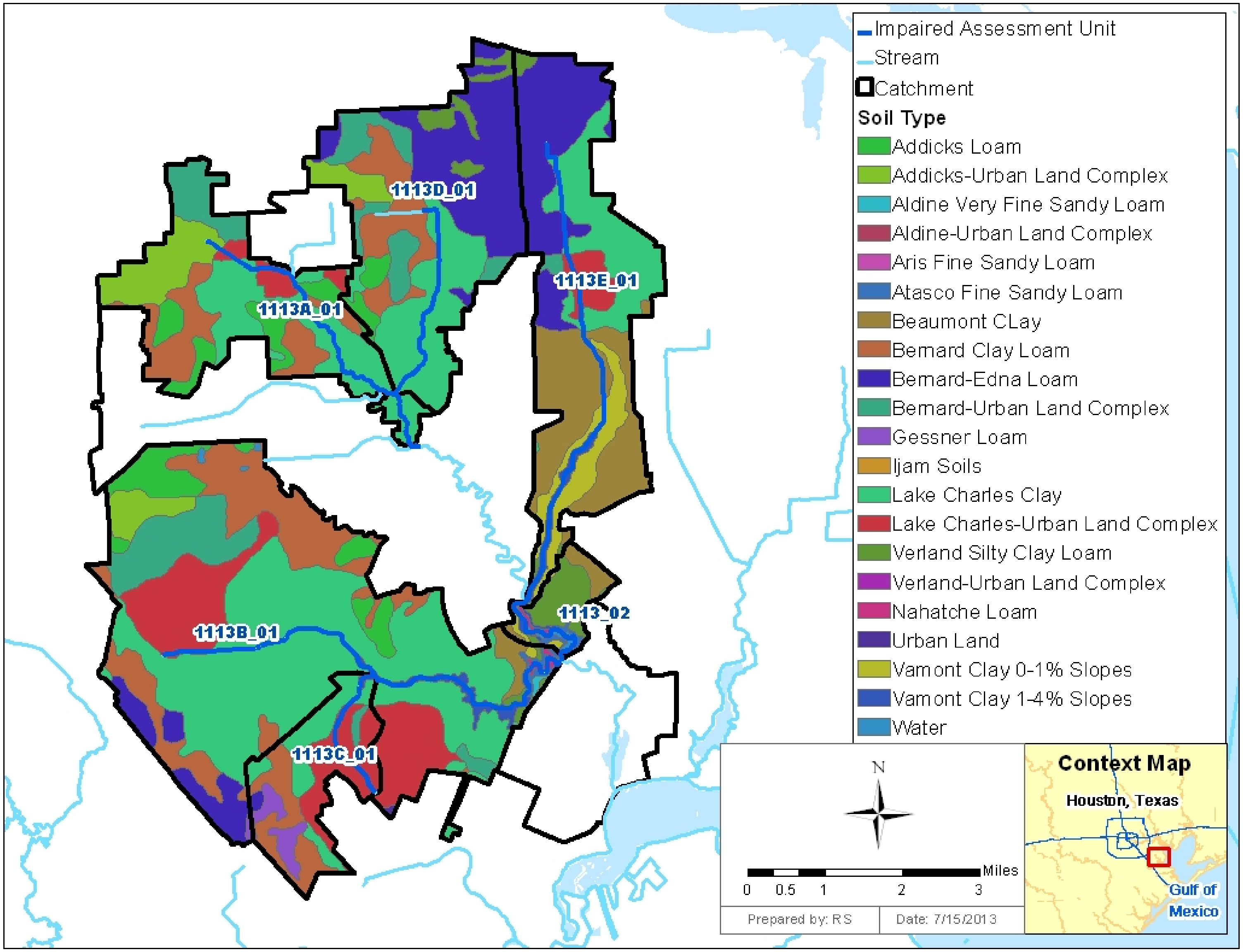

Figure 1-2: Armand Bayou Region Soil Types

1.2.2 Land Cover

As previously noted, the northern and southwestern portions of the Armand Bayou watershed are heavily developed while the lower and middle regions are sparsely developed. Table 1-5 summarizes the acreages and the corresponding percentages of the land cover categories for the contributing subwatershed associated with each impaired assessment unit in the Armand Bayou Watershed. The land cover data were retrieved from the National Oceanic and Atmospheric Administration (2011) land cover database obtained from Houston-Galveston Area Council. The total acreage of each segment in Table 1-5 corresponds to the watershed delineation in Figure 1-3. The predominant land cover category in this watershed is developed land (between 9% and 99%), followed by woody wetlands (between 0% and 66%) and hay/pasture (between 0% and 11%). Open water and bare/transitional land account for less than 10 percent of the assessment units.

Table 1-6: Aggregated Land Cover Summaries by Assessment Unit

Aggregated Land Cover Category	Segment Name and Assessment Unit ID					
	Armand Bayou Tidal	Armand Bayou Above Tidal	Horsepen Bayou Tidal	Unnamed Tributary to Horsepen Bayou	Willow Springs Bayou	Big Island Slough
Assessment Unit	**1113_02**	**1113A_01**	**1113B_01**	**1113C_01**	**1113D_01**	**1113E_01**
Acres of Open Water	68	41	117	0	38	61
Acres of Developed, Open Space	27	631	2,978	215	1,089	869
Acres of Developed, Low Intensity	11	809	1,343	327	783	745
Acres of Developed, Medium Intensity	10	1,178	2,534	1,032	1,607	1,293
Acres of Developed, High Intensity	12	511	679	190	392	483
Acres of Barren Land	15	10	33	0	25	32
Acres of Deciduous Forest	9	50	312	7	32	81
Acres of Evergreen Forest	29	1	22	0	15	20
Acres of Mixed Forest	3	3	11	0	2	44
Acres of Shrub/Scrub	2	39	344	0	55	47
Acres of Herbaceous	22	96	489	5	286	313
Acres of Hay/Pasture	0	162	1,143	0	511	271
Acres of Cultivated Crops	0	5	0	0	1	1
Acres of Woody Wetlands	443	152	662	0	34	842
Acres of Emergent Herbaceous Wetlands	22	0	0	0	0	3

Aggregated Land Cover Category	Segment Name and Assessment Unit ID					
	Armand Bayou Tidal	Armand Bayou Above Tidal	Horsepen Bayou Tidal	Unnamed Tributary to Horsepen Bayou	Willow Springs Bayou	Big Island Slough
Assessment Unit	**1113_02**	**1113A_01**	**1113B_01**	**1113C_01**	**1113D_01**	**1113E_01**
Watershed Area (acres)	**673**	**3,688**	**10,667**	**1,776**	**4,870**	**5,105**
Percent Open Water	10%	1%	1%	0%	1%	1%
Percent Developed, Open Space	4%	17%	28%	12%	22%	17%
Percent Developed, Low Intensity	2%	22%	13%	19%	16%	15%
Percent Developed, Medium Intensity	2%	32%	24%	58%	33%	25%
Percent Developed, High Intensity	2%	14%	6%	11%	8%	10%
Percent Barren Land	2%	0%	0%	0%	1%	1%
Percent Deciduous Forest	1%	1%	3%	0%	1%	2%
Percent Evergreen Forest	4%	0%	0%	0%	0%	0%
Percent Mixed Forest	1%	0%	0%	0%	0%	1%
Percent Shrub/Scrub	0%	1%	3%	0%	1%	1%
Percent Herbaceous	3%	3%	5%	0%	6%	6%
Percent Hay/Pasture	0%	5%	11%	0%	10%	5%
Acres of Cultivated Crops	0%	0%	0%	0%	0%	0%
Percent Woody Wetlands	66%	4%	6%	0%	1%	16%
Percent Emergent Herbaceous Wetlands	3%	0%	0%	0%	0%	0%

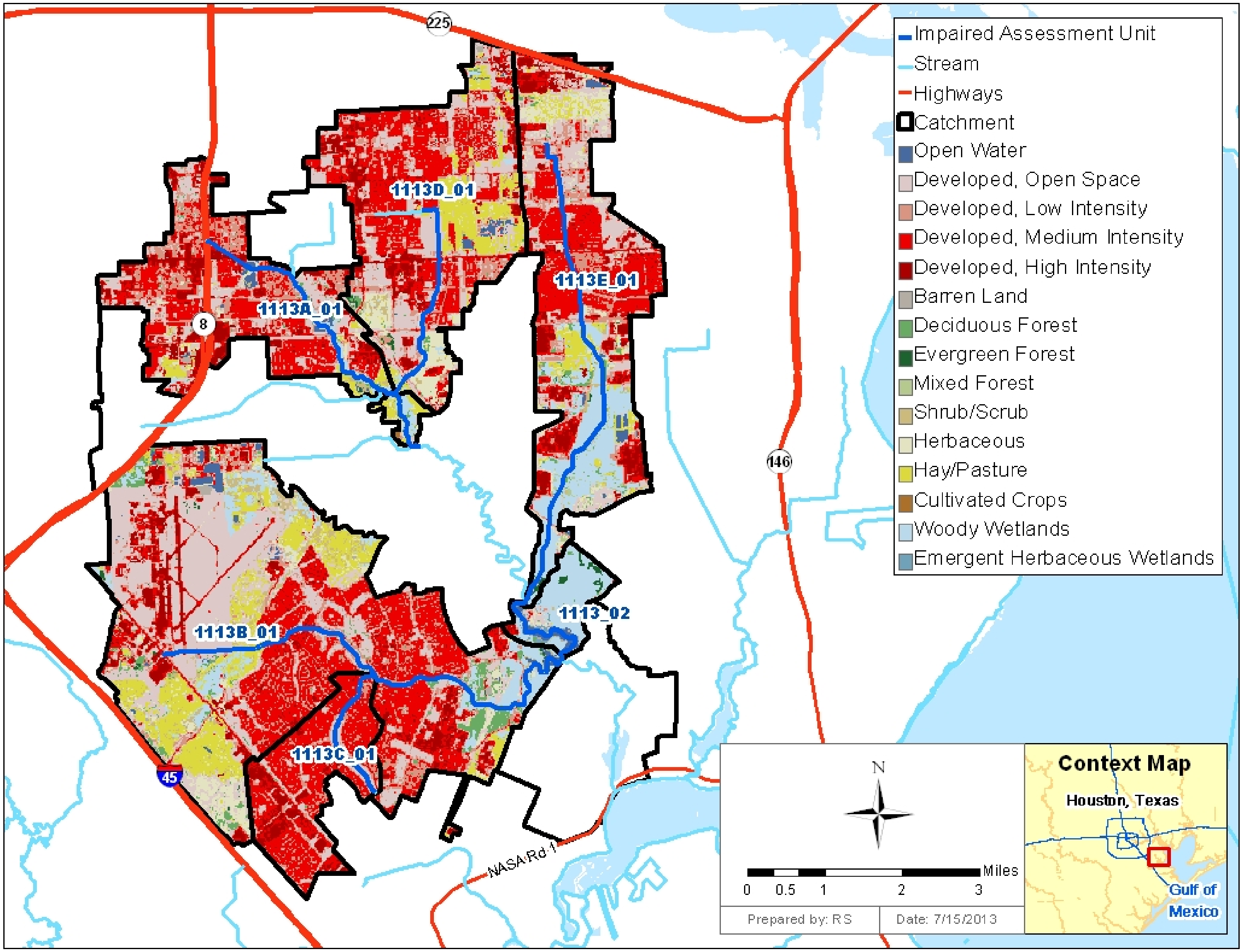

Figure 1-3: Land Cover Map

1.2.3 Precipitation

There are six rain gages located within the watershed (Figure 1-4) and two additional gages just outside the watershed boundaries that were used in this study. The gages are maintained by the Harris County Office of Homeland Security and Emergency Management (HCOEM). Table 1-6 summarizes total annual rainfall for the eight gages for a 13-year period. It should be noted that two gages, Gage 260 and Gage 640, were not operational until 2005. The region has high levels of humidity and receives annual precipitation ranging between 46.2 and 52.6 inches per year as shown in the table. Based on data for the period 2000 to 2012, the watershed average is around 49.9 inches per year.

To evaluate the distribution of rainfall across the watershed, Thiessen polygons were developed for each rainfall gage as shown in Figure 1-4. In general, coastal areas reported higher average rainfall than those areas farther inland. Average rainfall by subwatershed was also calculated and summarized in Table 1-7. Average rainfall amounts ranged from 46.6 inches in Armand Bayou Above Tidal watershed to 52.0 inches in Armand Bayou Tidal watershed.

To supplement the HCOEM rainfall data, annual average precipitation data were also compiled for the time period 1981 to 2010 based on the national data set from PRISM Group (PRISM Group 2006) summarized in Table 1-8. The annual average precipitation values for each subwatershed derived from PRISM in this portion of Texas range between 54.73 and 55.78 inches per year. The PRISM data indicate a slightly higher average annual precipitation for the Armand Bayou Watershed than the rainfall gages of the HCOEM, likely due to the drought in recent years (2010-2011) that may be skewing the rainfall totals lower. Therefore, the PRISM average values were used to support the development of flow duration curves described later in this document (Section 4).

Table 1-7: Annual Totals at HCOEM Rainfall Gages in Armand Bayou Watershed

Gage number	Year													Average
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	
Gage 140	47.1	69	70.3	42.5	60	35	65.8	72.1	32.9	27.7	60.5	25.1	54.0	50.9
Gage 210	53.2	75.6	67.7	53.3	56.7	35.5	52.5	67.0	39.5	33.1	47.2	25.4	53.5	50.8
Gage 220	44.4	76.1	63.7	44.2	56.6	27	61.2	70.1	47.5	50.4	49.7	26.4	40.6	50.6
Gage 230	33	82.1	59.3	43.4	60	36.2	62.5	77.5	49.3	56.4	47.4	26.4	50.4	52.6
Gage 240	37.8	65.1	65.4	46.3	58.6	31.2	58.4	74.7	42.2	44.2	40.9	23.4	53.7	49.4
Gage 250	40.7	69.6	64.2	50.3	58.6	35.8	56.6	72.2	29.3	61.6	55.1	27.0	56.1	52.1
Gage 270	N/A	N/A	N/A	N/A	N/A	35.4	59.9	75.4	46.1	34.2	43.3	25.5	50.0	46.2
Gage 640	N/A	N/A	N/A	N/A	N/A	38.6	62.3	81.0	41.5	37.7	42.6	22.7	47.2	46.7
Average rainfall across watershed (inches)														**49.9**

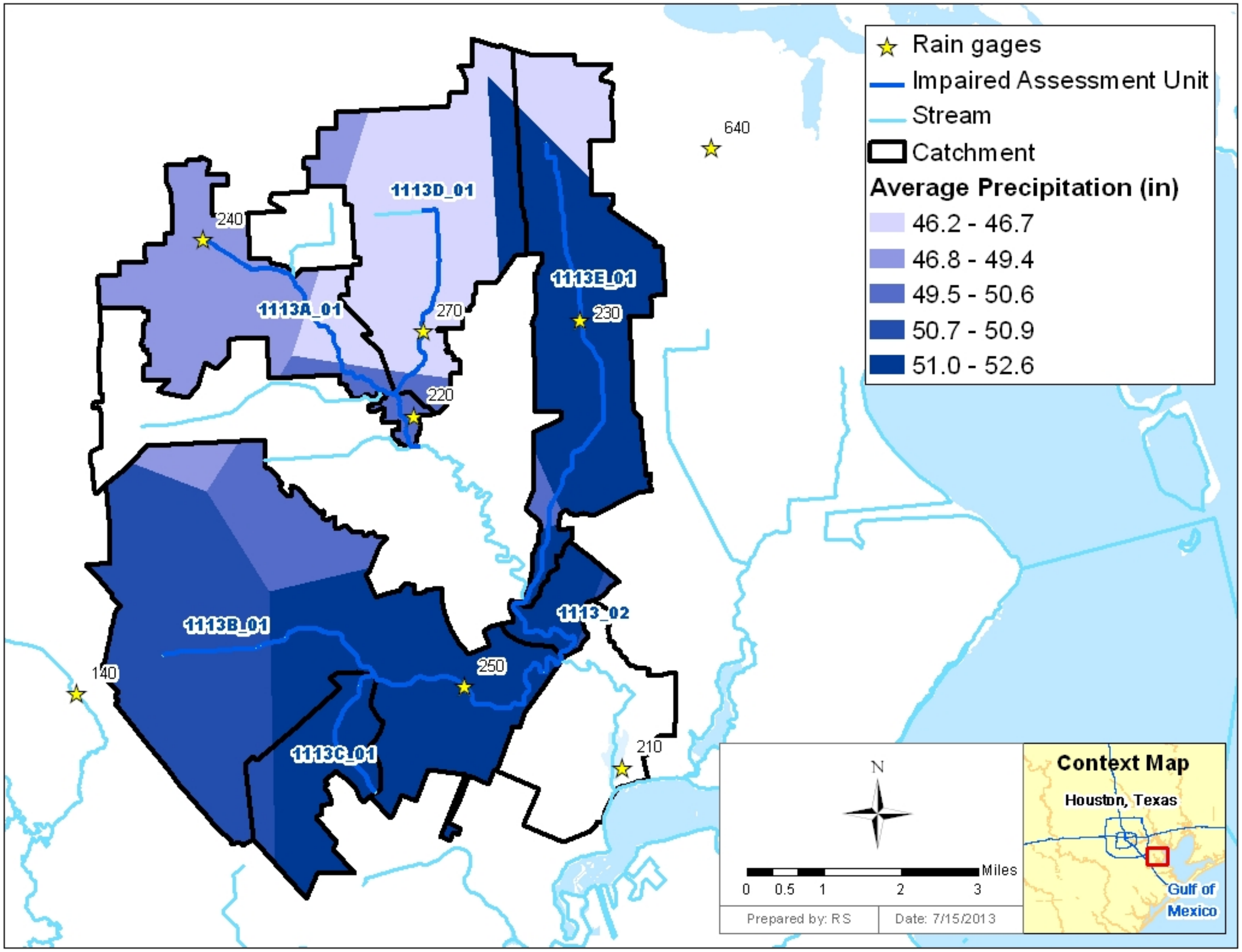

Figure 1-4: HCOEM Precipitation Map

Table 1-8: Average Annual HCOEM Precipitation in Armand Bayou Subwatersheds, 2000-2013

Segment Name	Assessment Unit	Average Annual (Inches)
Armand Bayou Tidal	1113_02	52.0
Armand Bayou Above Tidal	1113A_01	46.6
Horsepen Bayou Tidal	1113B_01	51.2
Unnamed Tributary to Horsepen Bayou	1113C_01	51.9
Willow Springs Bayou	1113D_01	50.3
Big Island Slough	1113E_01	51.8

Table 1-9: PRISM Annual Average Precipitation, 1981-2010

Segment Name	Assessment Unit	Average Annual (Inches)
Armand Bayou Tidal	1113_02	55.8
Armand Bayou Above Tidal	1113A_01	54.7
Horsepen Bayou Tidal	1113B_01	55.4
Unnamed Tributary to Horsepen Bayou	1113C_01	55.8
Willow Springs Bayou	1113D_01	54.8
Big Island Slough	1113E_01	55.2

Source: PRISM Group 2006

1.2.4 Ambient Water Quality

Considerable amounts of ambient water quality data are available to support water quality assessment and development of TMDLs for segments in the Armand Bayou Watershed. Historical indicator bacteria data for the period 2000 to 2012 were obtained from the TCEQ Surface Water Quality Monitoring Information System (SWQMIS) database. Seventy percent of the data correspond to *Escherichia coli* samples (608 samples), 29 percent correspond to enterococci samples (253 samples), while 1 percent correspond to fecal coliform samples (13 samples).

Table 1-9 summarizes the historical ambient water quality data for indicator bacteria (2000-2012) for select TCEQ Water Quality Monitoring (WQM) stations in the Armand Bayou Watershed. Figure 1-5 shows the locations of the WQM locations with indicator bacteria data. The complete ambient water quality data set for bacteria used to prepare Table 1-9 is provided in Appendix A. Table 1-9 presents the number of indicator bacteria samples, as well as the geometric mean of the concentrations for each indicator, and the number and percentage of single sample exceedances of the Texas SWQS. A more in-depth discussion of the analysis of this data set is provided in Subsections 2.3 and 2.4.

Table 1-10: Historical Water Quality Data for TCEQ Stations from 2000 to 2012

Assessment Unit	Station ID	Indicator Bacteria	Geometric Mean Concentration (MPN/100ml)	Number of Samples	Number of Samples Exceeding Single Sample Criterion	% of Samples Exceeding
1113_02	11503	EC	271.4	35	16	45.7%
		ENT	42.8	110	32	29.1%
1113A_01	11404	EC	204.6	111	37	33.3%
	11405	EC	56.3	5	0	0.0%
	17488	EC	1,179.3	82	57	69.5%
1113B_01	11409	EC	205.8	37	12	32.4%
		ENT	58.4	87	26	29.9%
	17317	ENT	64.7	31	9	29.0%
1113C_01	17485	EC	215.1	108	34	31.5%
1113D_01	17487	EC	744.0	109	74	67.9%
1113E_01	17486	EC	608.7	105	65	61.9%

EC: E coli, ENT: enterococci
Geometric Mean Criteria: 126 MPN/100 ml for EC, 35 MPN/100 ml for ENT.
Single Sample Criteria: 399 MPN/100 ml for EC, 104 MPN/100 ml for ENT.
Highlighted stations are tidally influenced.
Geometric mean concentrations were calculated assuming one-half the value of any concentration reported as less than the detection limit

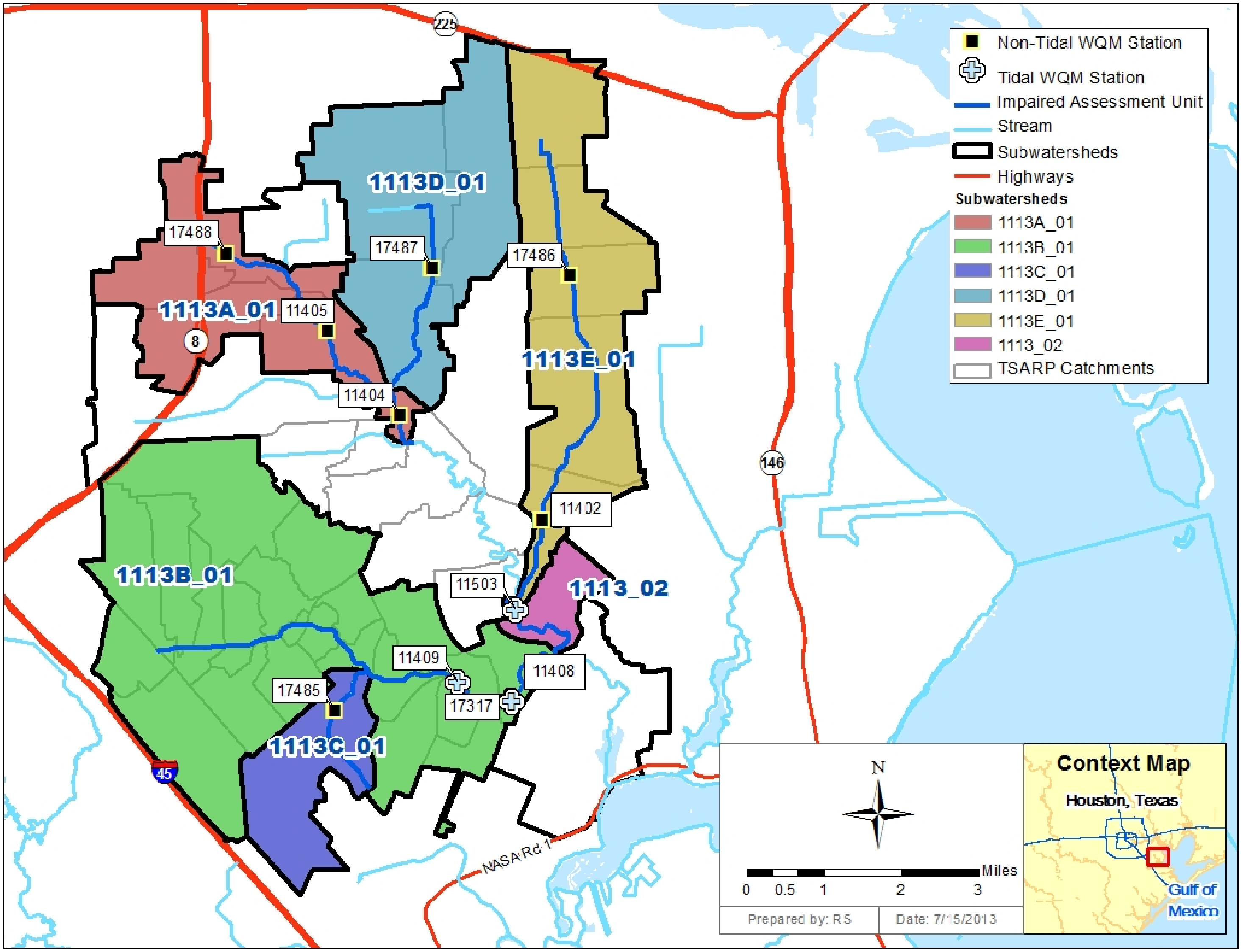

Figure 1-5: WQM Station Locations

1.2.5 Stream Flow Data

Stream flow data is key information when conducting water quality assessments such as TMDLs. The U.S. Geological Survey (USGS) does not maintain any current flow gages in the Study Area. To address this deficiency, flow projections were developed for the freshwater streams in the Armand Bayou Watershed using long-term flow records from USGS gage stations in surrounding watersheds as will be described in Appendix F.

1.2.6 Tide Data

Tide data were compiled to support the assessment and modeling of bacteria loading in the tidal segments of Armand Bayou. There are no tide gages currently located in Armand Bayou Watershed, however there is some significant historical tide data for the area. The closest gages that provide data regarding tides are as follows:

- The Texas Coastal Ocean Observation Network (TCOON) operated Station 502 near the mouth of Armand Bayou at Clear Lake Park. This gage had been in operation since 1991 but was damaged in Hurricane Ike and is no longer active as of September 13, 2008.
- The USGS operates Gage 08077637 at the mouth of Clear Lake into Galveston Bay. This gage is the next closest tide gage for the area. This gage has been in operation since 2007 and continues to operate at this time.

Data from these sites were plotted and are presented in Figure 1-6. As shown in the Figure, the tide at the TCOON gage is on average 5.05 ft higher than the water level reported at the USGS gage at the mouth of Clear Lake. A spreadsheet of these data are provided in Appendix C.

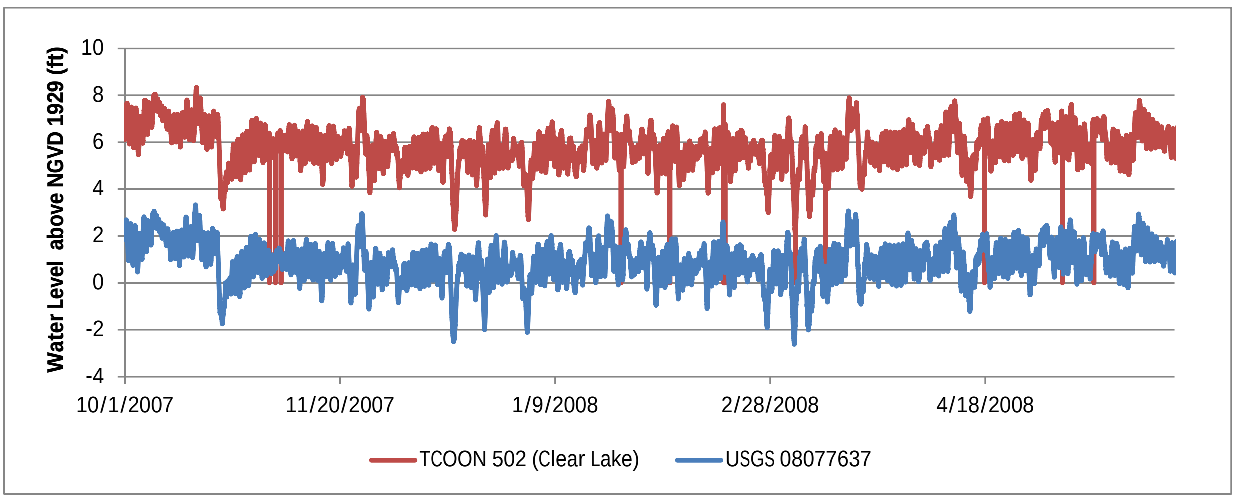

Figure 1-6: Tide Data Near Armand Bayou Watershed (TCOON Station 502 and USGS Gage 08077637)

1.3 Armand Bayou Seasonality

Seasonal differences in indicator bacteria concentrations were assessed by comparing historical bacteria concentrations collected in the warmer months versus those collected during the cooler months. The monthly average temperatures for Houston obtained from NOAA (Table 1-12) and were used to divide the data sets into warmer (25 – 29°C) and cooler months (12 – 21°C). Based on these temperature ranges, November, December, January, February, and March were considered the cooler months; May, June, July, August, and September were warmer months.

Table 1-11: Average Monthly Temperatures for Houston Hobby AP, TX (1981-2010)

Month	Daily Max (°C)	Daily Min (°C)	Daily Mean (°C)	Classification
Jan	17.4	7.3	12.4	Cool
Feb	19.5	9.2	14.3	Cool
Mar	23.1	12.7	17.9	Cool
Apr	26.3	15.9	21.1	n/a
May	29.9	20.1	25	Warm
Jun	32.8	23.1	27.9	Warm
Jul	34.2	24.1	29.2	Warm
Aug	34.1	24.1	29.1	Warm
Sep	31.8	22	26.9	Warm
Oct	27.8	16.8	22.3	n/a
Nov	22.5	11.9	17.2	Cool
Dec	18.6	8.2	13.4	Cool

Note: Temperature values from NOAA Houston Hobby Station (degrees Fahrenheit) have been converted to degrees Celsius.
http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/climate-normals/1981-2010-normals-data

To determine if there was a statistically significant difference between cool and warm months, a *t*-test was conducted on log transformed data between the warmer months and cooler months for WQM stations with six or more bacteria samples. Geometric means were also calculated for the warmer and cooler months. Table 1-13 shows seasonal variation for two stations for *E coli* and enterococci in addition to *E coli* only at several other stations.

For *E coli*, two of the four stations with six or more samples exhibited higher geometric mean concentrations for the colder months than the warmer months. No station showed statistically significant differences at the 95% confidence interval between the warmer and cooler months. For enterococci, both stations have slightly higher geometric mean concentrations during the cooler months, but neither difference was statistically significant.

Table 1-12: Seasonal Differences for *E coli* and enterococci Concentrations

Segment	Station ID	Indicator	Warm Months		Cold Months		*p*-value
			n	Geomean (MPN/100 ml)	n	Geomean (MPN/100 ml)	
1113_02	11503	EC	5	87.9	4	871.9	0.13
1113_02	11503	ENT	33	26.5	34	32.8	0.64
1113B_01	11409	ENT	32	38.8	34	49.5	0.66
1113C_01	17485	EC	24	200.1	31	194.0	0.94
1113D_01	17487	EC	25	443.3	31	647.4	0.35
1113E_01	17486	EC	26	677.1	29	496.7	0.54

EC: E coli, ENT: enterococci; n = number of samples
Highlighted rows correspond to stations for which the warm and cold datasets are significantly different at a 95% confidence interval.
p-value is based on a t-test conducted at each station using single sample concentrations.
All concentrations are in counts/dL; values less than the detection limit were treated in calculations as one-half the detection lim,it.

CHAPTER 2
PROBLEM IDENTIFICATION AND WATER QUALITY TARGET

2.1 Pollutant of Concern: Characteristics of Bacterial Indicators

The contact recreation use is assigned to almost every designated water body in the State of Texas, although full support of the contact recreation use is not a guarantee that the water is completely safe of disease-causing organisms. The evolution of the contact recreation criteria currently used by Texas began with criteria first published in 1968 based on general studies done on lakes in the Midwest and New York using fecal coliform bacteria as an indicator of the potential presence of fecal contamination (USEPA 1986). The USEPA-recommended criteria for recreational waters in 1976 included a geometric mean criterion: no more than 200 counts/dL based on five samples collected over a 30-day period; and an instantaneous criterion: no more than 10 percent of the individual grab samples could exceed 400 counts/dL (USEPA 1986). Shortly thereafter, these recommended criteria were adopted by the State of Texas in its SWQSs. The fecal coliform criteria, and the studies on which they were based, were heavily criticized by the USEPA in 1986 (USEPA 1986) following an extensive program of epidemiology testing. During that decade, USEPA studies found that fecal coliform was not a good predictor of the risk of disease and recommended new tests and criteria. The USEPA recommended new criteria for swimming areas, using *E coli* and enterococci as new fecal indicator organisms, and incorporating the idea of varying criteria with the level of swimming use.

In Texas, three indicator bacteria have been analyzed in water samples collected to determine support of the contact recreation use: fecal coliform and *E coli* in freshwater and fecal coliform and enterococci in marine waters. Currently, *E coli* and enterococci bacteria are measured to determine the relative risk of contact recreation, depending on whether the water body is fresh or marine. The presence of these bacteria indicates that associated pathogens from the fecal waste of warm-blooded species (human or animal) may be reaching a body of water. High concentrations of certain bacteria in water indicate there may be an increased risk of becoming ill from recreational activities.

Texas water quality standards (WQS) for contact recreation allow exemptions for waterbodies where elevated bacteria concentrations frequently occur due to sources of pollution that cannot be reasonably controlled by the existing regulations, or where recreation is considered unsafe for other reasons, such as barge or ship traffic (e.g., the Houston Ship Channel), unrelated to water quality. This exemption and reclassification to less strict “noncontact recreation” standards has been applied to only a few waterbodies in Texas.

2.2 TCEQ Water Quality Standards for Contact Recreation

The TCEQ is responsible for administering provisions of the constitution and laws of the State of Texas to promote judicious use of and protection of the quality of waters in the state. Included in this responsibility is the continuous monitoring and assessment of water quality to evaluate compliance with SWQSs established within Texas Water Code, §26.023 and Title 30 Texas Administrative Code (TAC), §§307.1-307.10. Texas SWQS, 30 TAC 307.4, specify the designated uses and general criteria for all surface waters in the state.

This report focuses on six waterbodies within the Armand Bayou Watershed that are on the federal Clean Water Act §303(d) list because they do not support contact recreation use. Table 2-1 lists all the assessment units within Armand Bayou that are on the 2012 303(d) list and provides a description of those assessment units. Table 2-2 summarizes the designated uses and the applicable bacteria indicators used to assess the contact recreation use of each waterbody addressed in this report. Table 2-1 also identifies the year each waterbody was placed on the Texas' Clean Water Act §303(d) List for nonsupport of contact recreation use, the stream length in miles, and other designated uses for each waterbody. The TMDLs in this report only address the contact recreation use.

Table 2-1: Synopsis of Texas 2012 303(d) List

Assessment Unit	Segment Name	Description	Category	Year First Listed
1113_02	Armand Bayou Tidal	From the Horsepen Bayou confluence to the Big Island Slough confluence	5c	2006
1113A_01	Armand Bayou Above Tidal	From the upper segment boundary of Armand Bayou Tidal (point 0.8 km (0.5 miles) downstream of Genoa-Red Bluff Road) upstream to Beltway 8	5b	1998
1113B_01	Horsepen Bayou Tidal	From the Armand Bayou confluence to the SH3	5c	2006
1113C_01	Unnamed Tributary to Horsepen Bayou	From the Horsepen Bayou confluence to Reseda Drive	5c	2010
1113D_01	Willow Springs Bayou	From the Armand Bayou confluence to a point 2.8 km (1.8 mi) upstream to an unnamed tributary	5c	2010
1113E_01	Big Island Slough	From the Armand Bayou confluence upstream to a point 2.4 km (1.5 mi) north of Spencer Hwy	5c	2012

Table 2-2: Synopsis of Texas Integrated Report for the Armand Bayou Watershed

Assessment Unit	Segment Name	Parameter	Designated Use*				Year Impaired	Stream Length (miles)
			CR	AL	GU	FC		
1113_02	Armand Bayou Tidal	ENT	FS	NS	FS	NS	2006	1.8
1113A_01	Armand Bayou Above Tidal	*E coli*	NS	NS	NA	NA	1998	4.6
111B_01	Horsepen Bayou Tidal	ENT	NS	FS	NA	NA	2006	6.7
1113C_01	Unnamed Tributary to Horsepen Bayou	*E coli*	NS	FS	NA	NA	2010	2
1113D_01	Willow Springs Bayou	*E coli*	NS	FS	NA	NA	2010	2.9
1113E_01	Big Island Slough	*E coli*	NA	NA	NA	NA	2012	6.5

** CR: Contact recreation; AL: Aquatic Life; GU: General Use; F: Fish Consumption; ENT: enterococci, NS = Not Supporting; FS = Fully Supporting; NA= Not Assessed*

The excerpts below from Chapter 307, Texas SWQS stipulate how water quality data were assessed to determine support of contact recreation use as well as how the water quality targets are defined for each bacterial indicator. In addition to the specific requirements of §307.7 outlined below, the TMDLs for the Armand Bayou Watershed will also adhere to §307.5 of the SWQS which defines the antidegradation policy and procedures that apply to authorized wastewater discharges, TMDLs, waste load evaluations, and any other miscellaneous actions, such as those related to man-induced nonpoint sources of pollution, which may impact the water in the state.

Excerpted from 30 Texas Administrative Code (TAC) §307.7. Site-specific Uses and Criteria.

(a) Uses and numerical criteria are established on a site-specific basis in Appendices A,B,D,E,F and G of §307.10 of this title (relating to Appendices A - G). Site-specific uses and numerical criteria may also be applied to unclassified waters in accordance with §307.4(h) of this title (relating to General Criteria) and §307.5(c) of this title (relating to Antidegradation). Site-specific criteria apply specifically to substances attributed to waste discharges or human activities. Site-specific criteria do not apply to those instances in which surface waters exceed criteria due to natural phenomena. The application of site-specific uses and criteria is described in §307.8 of this title (relating to the Application of Standards) and §307.9 of this title (relating to the Determination of Standards Attainment).

(b) Appropriate uses and criteria for site-specific standards are defined as follows.

(1) Recreation. Recreational use consists of four categories – primary contact recreation, secondary contact recreation 1, secondary contact recreation 2, and noncontact recreation waters. Classified segments are designated for primary contact recreation unless sufficient site-specific information demonstrates that elevated concentrations of indicator bacteria frequently occur due to sources of pollution which cannot be reasonably controlled by existing regulations, wildlife sources of bacteria are unavoidably high and there is limited aquatic recreational potential, or primary or secondary contact recreation is considered unsafe for other reasons such as ship or barge traffic. In a classified segment where contact recreation is considered unsafe for reasons unrelated to water quality, a designated use of noncontact recreation may be assigned criteria normally associated with contact recreation. A designation of primary or secondary contact recreation is not a guarantee that the water so designated is completely free of disease-causing organisms. Indicator bacteria, although not generally pathogenic, are indicative of potential contamination by feces of warm blooded animals. The criteria for contact recreation are based on these indicator bacteria, rather than direct measurements of pathogens. Criteria are expressed as the number of bacteria per 100 milliliters (ml) of water (in terms of colony forming units, most probable number, or other applicable reporting measures). Even where the concentration of indicator bacteria is less than the criteria for primary or secondary contact recreation, there is still some risk of contracting waterborne diseases. Additional guidelines on minimum data requirements and procedures for evaluating standards attainment are specified in the TCEQ Guidance for Assessing and Reporting Surface Water Quality Data in Texas, as amended.

(A) Freshwater

(i) Primary contact recreation. The geometric mean criterion for E coli is 126 per 100 mL. In addition, the single samples criterion for E coli is 399 per 100 mL.

(ii) Secondary contact recreation 1. The geometric mean criterion for E coli is 630 per 100 mL.

(iii) Secondary contact recreation 2. The geometric mean criterion for E coli is 1,030 per 100 mL.

(iv) Noncontact recreation. The geometric mean criterion for E coli is 2,060 per 100 mL.

(v) For high saline inland water bodies where enterococci is the recreational indicator for instream bacteria sampling at all times for the classified water body and for the unclassified water bodies that are within the watershed of that classified segment, unless it is demonstrated that an unclassified water body is not high saline. E coli is the applicable recreational indicator for instream bacteria sampling at all times for unclassified water bodies where conductivity values indicate that the water bodies are not high saline. For high saline water bodies with primary contact recreation, the geometric mean criterion for enterococci is 33 per 100 ml and the single sample criterion is 78 per 100 ml. For high saline inland waters with secondary contact recreation 1, the geometric mean criterion for enterococci is 165 per 100 ml. For high saline inland waters with secondary contact recreation 2, the geometric mean criterion for enterococci is 270 per 100 ml. For high saline inland water bodies with noncontact recreation, the geometric mean criterion for enterococci is 540 per 100 ml.

(B) Saltwater

(i) Primary contact recreation. The geometric mean criterion for enterococci is 35 per 100 mL. In addition, the single sample criterion for enterococci is 104 per 100 mL.

(ii) Secondary contact recreation 1. A secondary contact recreation 1 use for tidal streams and rivers can be established on a site-specific basis in §307.10 of this title if justified by a use-attainability analysis and the water body is not a coastal recreation water as defined in the Beaches Environmental Assessment and Coastal Health Act of 2000 (BEACH Act). The geometric mean criterion for enterococci is 175 per 100 mL.

(iii) Noncontact recreation. A noncontact recreation use for tidal streams and rivers can be established on a site-specific basis in §307.10 of this title if justified by a use-attainability analysis and the water body is not a coastal recreation water as defined in the BEACH Act. The geometric mean criterion for enterococci is 350 per 100 mL.

(C) Fecal coliform bacteria. Fecal coliform bacteria can be used as an alternative instream indicator of recreational suitability in high saline inland water bodies where enterococci is the designated recreational indicator in Appendix A of §307.10 of this title for two years after the adoption of this title to allow time to collect sufficient data for enterococci. Fecal coliform criteria for high saline inland water bodies are as follows:

(i) Primary contact recreation. The geometric mean criterion for fecal coliform is 200 per 100 mL. In addition, single sample criterion for fecal coliform is 400 per 100 mL.

(ii) Secondary contact recreation 1 and 2. The geometric mean criterion for fecal coliform is 1,000 per 100 mL.

(iii) Noncontact recreation. The geometric mean criterion for fecal coliform is 2,000 per 100 mL.

(D) Swimming advisory programs. For areas where local jurisdictions or private property owners voluntarily provide public notice or closure based on water quality, the use of any single sample or short-term indicators of recreational suitability are selected at the discretion of the local managers of aquatic recreation. Guidance for single-sample bacterial indicators is available in the USEPA document entitled Ambient Water Quality Criteria for Bacteria - 1986. Other short-term indicators to assess water quality suitability for recreation -- such as measures of streamflow, turbidity, or rainfall -- may also be appropriate.

A minimum of 10 samples from the last seven years or the most recently collected 10 samples for up to ten years are used to determine use support

As stipulated in 2010 *Guidance for Assessing and Reporting Surface Water Quality in Texas* (TCEQ 2010), utilization of the geometric mean to determine compliance for any of the bacterial indicators depends on the collection of a *minimum of 10 samples from the last seven years or the most recently collected 10 samples for up to ten years are used to determine use support*. The 2010 *Guidance for Assessing and Reporting Surface Water Quality in Texas* (TCEQ 2010) specifically states the following*:*

- *Ten samples will also be required for listing and delisting water bodies for which the assessment method is based on an average. Larger sample sizes increase the state's confidence that impairments are not missed. Although we will use more than 10 samples, if available, it is not reasonable at this time to require more than 10 samples for a minimum data set, given the monitoring resources and currently available data.*
- *The 2010 assessment period of record for the last seven years is December 1, 2001 through November 30, 2008. Samples from these seven years are evaluated when available, and if necessary, the most recent samples collected in the preceding three years (December 1, 1998 through November 30, 2000) can also be included to meet the requirements for minimum sample*

2.3 Problem Identification

Pursuant to §303(d) of the federal Clean Water Act, states must establish TMDLs for pollutants contributing to violations of WQSs. Table 2-2 identifies the waterbodies requiring TMDLs identified in Category 5 of the 2012 Texas Water Quality Inventory and §303(d) List (TCEQ 2012). Between 1996 and 2010 as the TCEQ WQSs and water quality assessment method were modified and additional water quality data were collected throughout the Armand Bayou Watershed, areas of impairment were added to the §303(d) List. Table 2-2 lists the TCEQ WQM stations from which ambient water quality data were summarized to support the decision to place these waterbodies on the TCEQ 303(d) List. The waterbodies requiring the TMDLs were first listed in 1998. The locations of these WQM stations are displayed in Figure 2-1 and on this map each station is designated as a tidal or non-tidal station.

A number of changes have occurred in the past 10 years that warrant refinements in how indicator bacteria data are used to support water quality assessments and TMDL development in Texas. Some key factors that influence which indicator bacteria to use for water quality assessment and TMDL development and the period of record to use include:

- Changes in land cover and locations of Texas Pollution Discharge Elimination System (TPDES)-permitted facilities
- changing the indicator bacteria in the 2000 TCEQ surface water quality standards (SWQS) from fecal coliform to *E coli* for fresh water, and enterococci for marine waters
- Refinements in the TCEQ surface water quality monitoring procedures
- Changes in the TCEQ guidance, *Assessing and Reporting Surface Water Quality in Texas*

As a result of these evolving factors in the water quality management arena associated with the protection and maintenance of contact recreation use, the historical data set used to support the TMDLs in this report have been narrowed, wherever possible, to utilize only *E coli* and enterococci data from 2003 through 2011.

Table 2-3: Water Quality Monitoring Stations Used for 303(d) Listing Decision

Assessment Unit	Water Body	Description	Monitoring Station IDs	Year
1113_02	Armand Bayou Tidal	Armand Bayou Tidal at Bay Area Blvd north of NASA at middle of median between 2 bridges eastern shore	11503	2006
1113A_01	Armand Bayou Above Tidal	Armand Bayou Above Tidal 77 meters upstream of Dedman Street/West Pasadena Blvd in southeast Houston	17488	1998
		Armand Bayou at Fairmont Parkway along median at midpoint between bridges	11405	
		Armand Bayou at Genoa-Red Bluff Rd NE of Ellington AFB	11404	
1113B_01	Horsepen Bayou Tidal	Horsepen Bayou at Bay Area Blvd north of NASA	11409	2006
		Horsepen Bayou 1.4 km downstream of Bay Area Blvd 34m downstream of Middlebrook Dr. in southeast Houston	11408	
		Horsepen Bayou at Middlebrook Dr. in southeast Houston	17317	
1113C_01	Unnamed Tributary to Horsepen Bayou	Unnamed Tributary of Horsepen Bayou Tidal at Penn Hills	17485	2010
1113D_01	Willow Springs Bayou	Willow Spring at Bandridge Rd in southeast Houston	17487	2010
1113E_01	Big Island Slough	Big Island Slough at Hillridge Rd in southeast Houston	17486	2012
		Big Island Slough at Red Bluff Rd in southeast Houston mid-channel between the two bridges of divided road	11402	

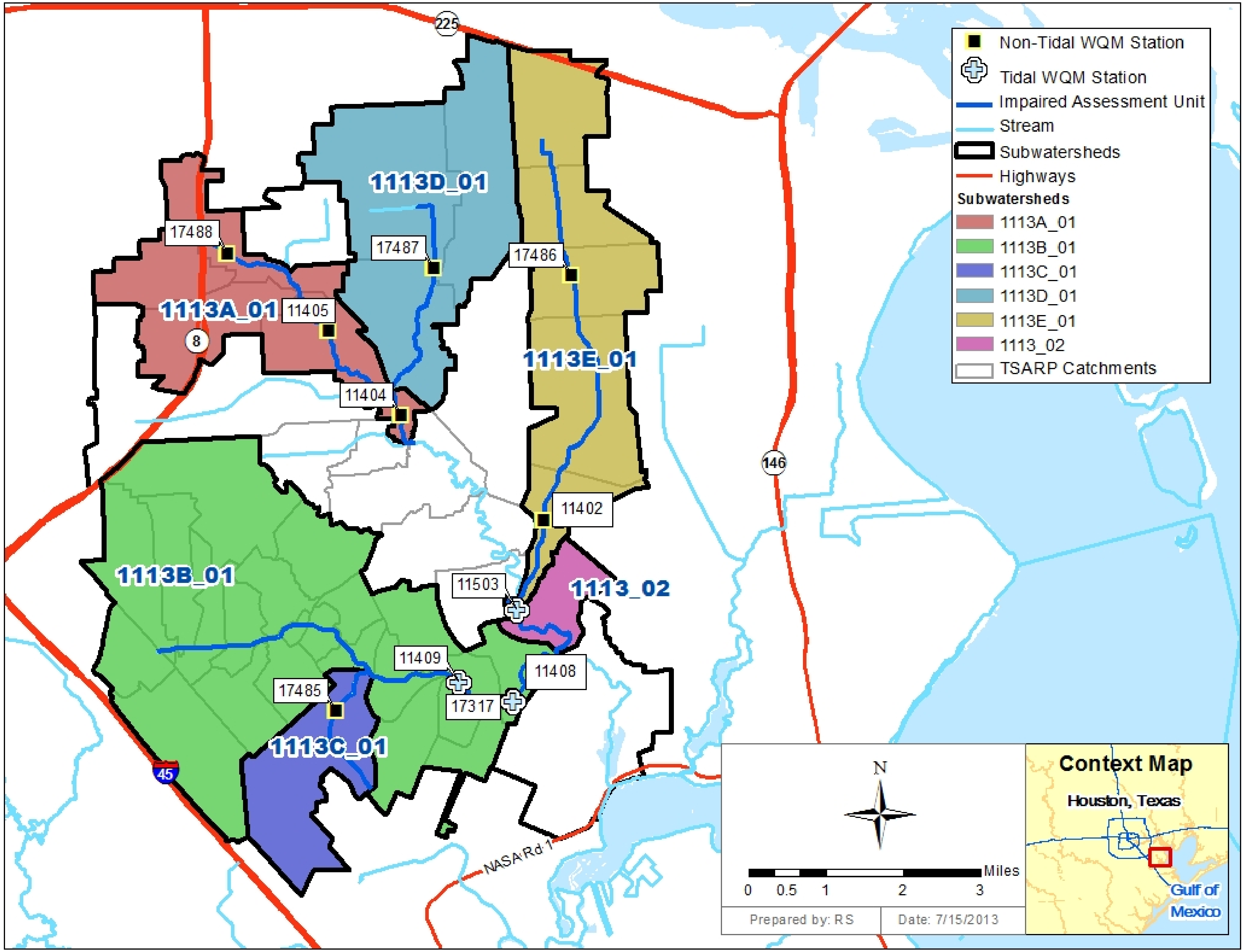

Figure 2-1: TCEQ WQM Stations in the Armand Bayou Watershed

2.4 Water Quality Targets for Contact Recreation

The Code of Federal Regulations (40 CFR §130.7(c)(1)) states that, "TMDLs shall be established at levels necessary to attain and maintain the applicable narrative and numerical water quality standards." The Texas SWQSs (TCEQ 2010) provide numeric and narrative criteria to evaluate attainment of designated uses. The basis for water quality targets for all TMDLs developed in this report will be the numeric criteria for bacterial indicators from the 2010 Texas SWQSs as described in Subsection 2.2 above. *E coli* is the preferred indicator bacteria for assessing contact recreation use in freshwater, and enterococci is the preferred indicator bacteria in saltwater.

Several studies have been performed by the USEPA that show a stronger link between the concentrations of *E coli* and enterococci and the concentrations of fecal pathogens than the previous standard, fecal coliform. The USEPA studies found that in freshwater streams, *E coli* concentrations were the strongest predictor of illness following contact recreation. The TCEQ adopted the limit of 399 per dL for single samples of *E coli* and a geometric mean limit of 126 per dL for waterbodies that have been designated for contact recreation use. Within tidal streams and saltwater bodies, however, the USEPA determined that enterococci concentrations were the strongest predictor of illness. The TCEQ adopted a limit of 104 per dL for enterococci in any single sample, and a limit of 35 per dL for the geomean of all samples at any location for enterococci concentrations within a tidal stream designated for contact recreation uses (TCEQ 2010).

The water quality target for the TMDLs for freshwater segments is to maintain concentrations below the geometric mean criterion of 126 counts per dL for *E coli*. The water quality target for the TMDLs for tidal (saltwater) segments is to achieve concentrations of enterococci below the geometric mean criterion of 35 counts per dL. The tidal segments are Armand Bayou Tidal and Horsepen Bayou. Maintaining the geometric mean criterion for each indicator bacteria is expected to be protective of the single sample criterion also and therefore will ultimately result in the attainment of the contact recreation use. TMDLs will be based on a percent reduction goal required to meet the geometric mean criterion.

The water quality target for each waterbody will incorporate an explicit 5 percent margin of safety (MOS). For example, if *E coli* is utilized to establish the TMDL, then the water quality target would be 379 counts/dL, 5 percent lower than the single sample water quality criterion (399 counts/dL) and the geometric mean water quality target would be 120 counts/dL, 5 percent lower than the criterion value (126 counts/dL). For enterococci, the single sample water quality target would be 74 counts/dL and the geometric mean water quality target would be 31 counts/dL, both 5 percent lower than the criterion values.

For non-tidal segments, each water quality target will be used to determine the allowable bacteria load that is derived by using the actual or estimated flow record multiplied by the instream criteria minus a 5 percent MOS. For tidal segments, a mass-balance model will be used to determine the maximum amount of loading discharged to the water bodies that result in meeting the geometric mean criteria throughout the length of the segment.

CHAPTER 3
POLLUTANT SOURCE ASSESSMENT

To support TMDL development, a pollutant source assessment attempts to characterize known and suspected sources of pollutant loading to impaired waterbodies. Pollutant sources within a watershed are categorized and quantified to the extent that information is available. Fecal bacteria such as *E coli* and Enterococcus originate in the intestines of warm-blooded species (human and animal), and sources of bacteria may be point (permitted) or nonpoint (unregulated) in nature.

Point sources are permitted through the National Pollution Discharge Elimination System (NPDES) program. Some stormwater runoff may be permitted through NPDES as municipal separate storm sewer systems (MS4). Other unregulated sources of stormwater runoff that typically cannot be identified as entering a waterbody through a discrete conveyance at a single location are often referred to as nonpoint sources. For example, unregulated sources include land activities that contribute bacteria to surface water as a result of rainfall runoff or on-site sewage system facilities. For the TMDLs presented in this report, all sources of pollutant loading not regulated by a NPDES/TPDES permit are considered nonpoint sources. The following discussion describes what is known regarding permitted and unregulated sources of bacteria in the impaired watersheds.

3.1 Point Sources: NPDES/TPDES-Permitted Sources

Under 40 CFR, §122.2, a point source is described as a discernible, confined, and discrete conveyance from which pollutants are or may be discharged to surface waters. Under the Texas Water Code, TCEQ has adopted rules and procedures to issue permits to control the quantity and quality of discharges into or adjacent to waters of the state through the TPDES program. NPDES/TPDES-permitted facilities classified as point sources that may contribute bacteria loading to surface waters include:

- TPDES municipal wastewater treatment facilities (WWTF)
- TPDES industrial WWTF (stormwater and/or wastewater)
- TPDES municipal no-discharge WWTF
- TPDES regulated stormwater (municipal separate storm sewer systems)
- TPDES Concentrated Animal Feeding Operation (CAFO)

Point source discharges such as WWTFs could result in discharge of elevated concentrations of fecal bacteria if the plant is not properly maintained, is of poor design, or if flow rates exceed the treatment capability of the plant. Industrial WWTFs may contain fecal bacteria in their effluent. While no-discharge facilities do not discharge wastewater directly to a waterbody, it is possible that collection systems associated with these types of facilities may be a source of bacteria loading to surface waters. Permitted stormwater runoff from TPDES regulated discharge areas, called municipal separate storm sewer systems, may also contain high fecal bacteria concentrations. Finally, CAFOs are recognized by USEPA as significant potential source of pollution, and may have the potential to cause serious impacts to water quality if not properly managed.

Two watersheds in the Study Area, including Horsepen Bayou Tidal (1113B_01) and Big Island Slough (1113E_01) have NPDES/TPDES-permitted sources. A significant portion of the Study Area is regulated under the TPDES stormwater discharge permit jointly held by Harris County, HCFCD, City of Houston, and Texas Department of Transportation. There are no NPDES-permitted CAFOs within the Study Area.

3.1.1 Permitted Sources: NPDES/TPDES Wastewater Facility Point Source Discharges

There are four TPDES-permitted facilities in the watershed; two of which are permitted to discharge treated domestic wastewater continuously to surface waters addressed in these TMDLs. The other two facilities are do not discharge into surface waters. The location of all four facilities is shown in Figure 3-1 with additional details on each provided in Table 3-1. As shown in Table 3-1, the permitted flows associated with the two continuously discharging facilities range between 5 and 10 MGD. The two facilities permitted in the watershed that don't have continuous discharges include an industrial stormwater discharge from Equistar Chemicals and a City of Houston Sludge Plant that is a permitted as a no discharge facility. There are no WWTFs located in the following segments/assessment units: Armand Bayou Above Tidal (1113A_01), Willow Springs Bayou (1113D_01), Armand Bayou Tidal (1113_02), or Unnamed Tributary of Horsepen Bayou (1113C_01) watersheds. Horsepen Bayou (1113B_01) contains both WWTFs.

TPDES-permitted facilities that discharge treated wastewater are required by their permit to monitor their effluent for certain parameters. A summary of the discharge monitoring report (DMR) data for the two domestic facilities in the watershed is shown in Table 3-2. In addition, collecting fecal indicator bacteria data for In the Armand Bayou watershed, only TPDES facility 10495-152 collects such data. Table 3-2 provides a summary of the self-reporting data available for the two facilities in the Study Area, while Table 3-3 lists the number of reported monthly exceedances of the daily average concentration of 35 cfu/100 mL, and the number of reported daily exceedances of the daily maximum of 89 cfu/100 mL. As shown in the tables, Facility 10495-152 exceeded enterococci permit limits four times during the monitoring time frame.

The discharge monitoring data for each of the plants is presented in Appendix D.

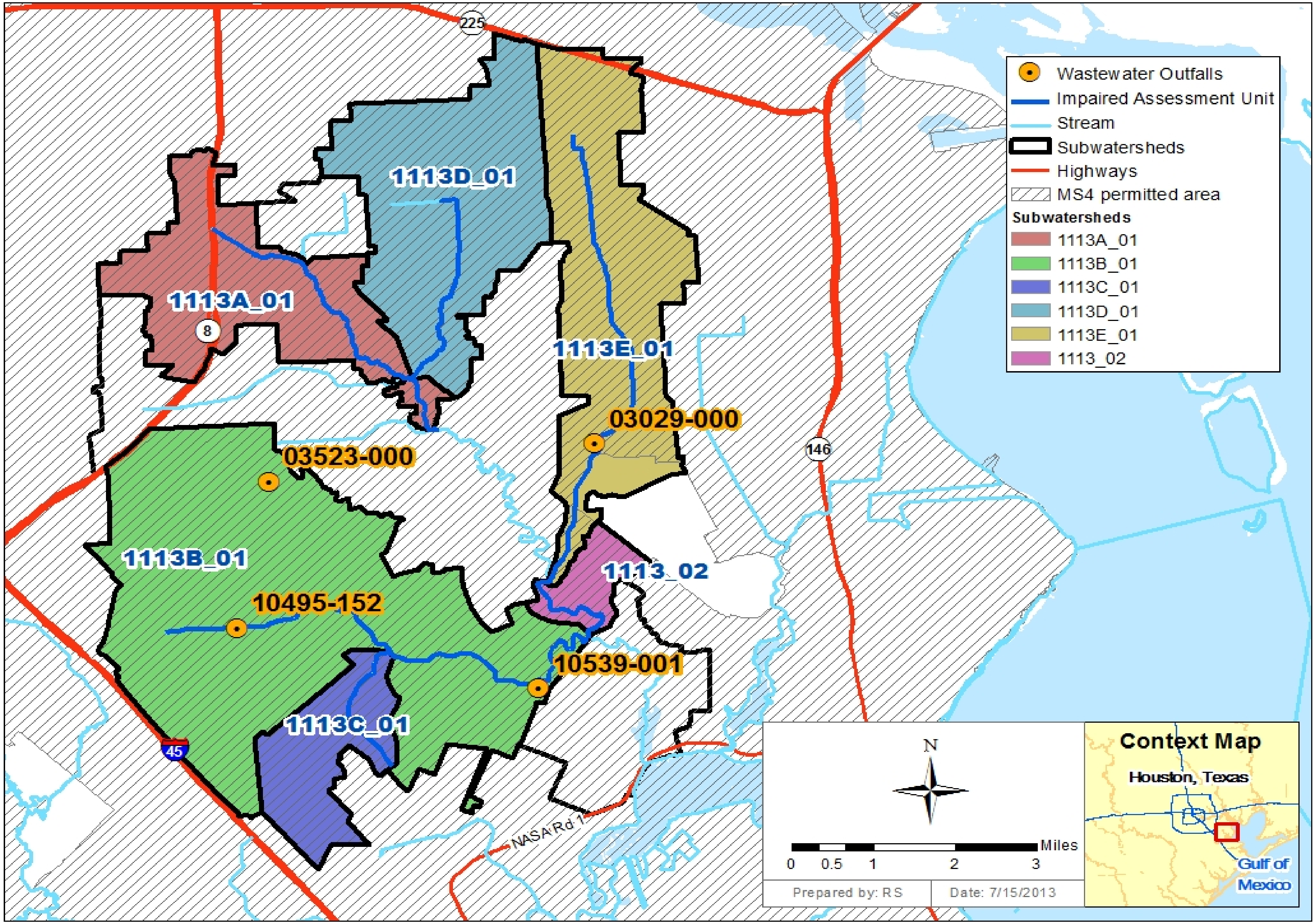

Figure 3-1: TPDES-Permitted Facilities in the Armand Bayou Watershed

Table 3-1: TPDES-Permitted Facilities in the Study Area

Assessment Unit	Receiving Water	TPDES Number	NPDES Number	Facility Name	Facility Type	DTYPE	Permitted Flow (MGD)	Average Monthly Flow (MGD)
1113B_01	Horsepen Bayou Tidal	10495-152	TX0069736	Metro Central WWTP	Sewerage Systems	W	5	1.44
1113B_01	Horsepen Bayou Tidal	10539-001	TX0022543	Robert T Savely Water Reclamation Facility	Sewerage Systems	W	10	5.58
1113B_01	Horsepen Bayou Tidal	03523-000	TXL005000	City of Houston Sludge Plant	Water Supply	*n/a*	*n/a*	*n/a*
1113E_01	Big Island Slough	03029-000	TX0103900	Equistar Chemicals Bayport Complex	Industrial Stormwater	*n/a*	*n/a*	*n/a*

Source: TCEQ Wastewater Outfall Shapefile, August 2013, EPA, ICIS monitoring data search August 2013
MGD = Millions of Gallons per Day; n/a = Not Applicable
TYPE: D = Domestic < 1 MGD; W=Domestic >= 1 MGD

Table 3-2: DMR Data for Permitted Wastewater Discharges (November 2003-May 2013)

TPDES Number	NPDES Number	Facility Name	Assessment Unit	Stream Name	Dates Monitored		# of Records	Monthly Average Flow (MGD)*	Permitted Flow (MGD)
					Start	End			
10495-152	TX0069736	Metro Central WWTP	1113B_01	Horsepen Bayou Tidal	11/30/03	5/31/13	110	1.44	5
10539-001	TX0022543	Robert T Savely Water Reclamation Facility	1113B_01	Horsepen Bayou Tidal	12/31/04	5/31/13	101	5.58	10

Source: EPA, ICIS monitoring data search August 2013
*Notes: n/a = Not Available, MGD = Millions of Gallons per Day, cfu = Colony Forming Unit; *there were several missing monthly flow data points; these gaps were filled by taking average of flows for the previous and subsequent months.*

Table 3-3: Enterococci Data for Permitted Wastewater Discharges (December 2009-May 2013)

Facility Name	TPDES Number	NPDES Number	No. Records	Avg Daily Average (cfu/100 mL)	Avg Monthly Maximum (cfu/100 mL)	Exceedances of Maximum Permit Limit (89 cfu/100 mL)		Exceedances of Average Permit Limit (35 cfu/100 mL)	
						Number	%	Number	%
Metro Central WWTP	10495-152	TX0069736	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*
Robert T Savely Water Reclamation Facility	10539-001	TX0022543	42	2.0	111.4	4	9.5%	0	*n/a*

Source: EPA, ICIS monitoring data search August 2013
Notes: MCMX = Measurement: Concentration Maximum, MCAV = Measurement: Concentration Average, n/a = Not Available

3.1.2 Permitted Sources: Sanitary Sewer Overflows

Sanitary sewer overflows (SSO) are overflows from sanitary sewers that most often result from blockages in the sewer collection pipes caused by tree roots, grease and other debris. Occurrences of SSOs are permit violations that must be addressed by the responsible TPDES permittee.

The TCEQ maintains a database of SSO data collected from wastewater operators in the Armand Bayou Watershed. TCEQ Region 12-Houston provided a database for SSO data in the Armand Bayou Watershed (Laird 2013). These data are included in Table 3-4.

As can be seen from Table 3-4, there have been approximately 95 sanitary sewer overflows reported in the Armand Bayou watershed since August 2003. The reported SSOs averaged 3,539 gallons per event.

The locations and magnitudes of the all reported SSOs within the Armand Bayou watershed are displayed in Figure 3-2. It is important to note that some facilities, such as the City of Deer Park WWTF and Little Cedar Bayou WWTF, provide wastewater service within the boundary of the Armand Bayou Watershed but the facilities themselves do not discharge to Armand Bayou. The WWTF service area boundaries are shown in Figure 3-2. These data are included in Appendix F and summarized in Table 3-4.

Table 3-4: Sanitary Sewer Overflow (SSO) Summary

Facility Name	NPDES Permit No.	Facility ID	Number of Occurrences	Date Range		Amount (Gallons)	
				From	To	Min	Max
Robert T. Savely WWTF	TX0022543	10539-001	51	8/22/03	5/14/13	6	19,200
Metro Central WWTF	TX0069736	10495-152	2	4/18/12	5/12/12	200	1000
City of Deer Park WWTF	TX0025321	10519-002	21	9/26/03	6/26/13	50	10,000
Little Cedar Bayou WWTF	TX0022799	10206-001	23	6/11/06	4/27/13	15	72,000

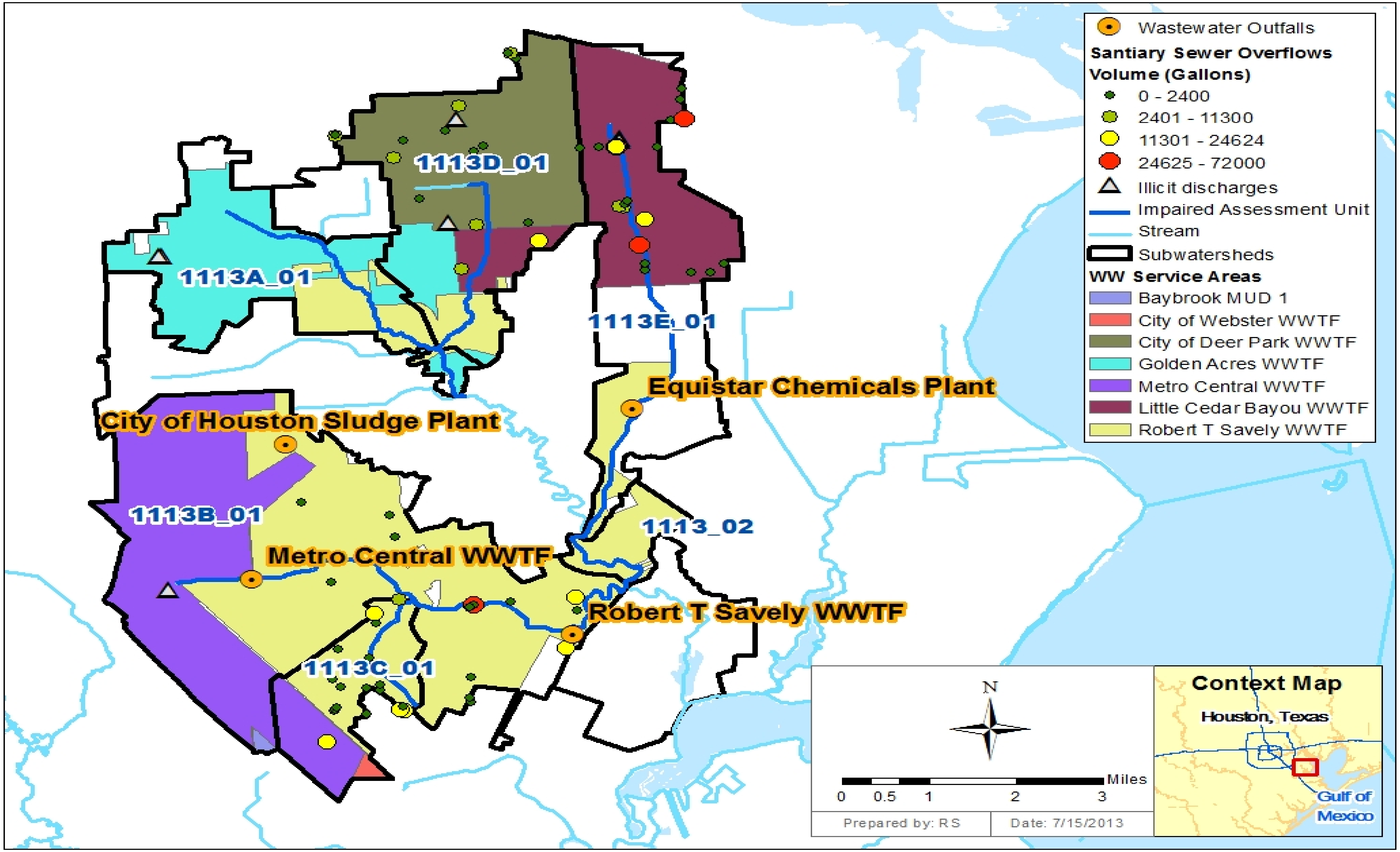

Figure 3-2: Sanitary Sewer Overflow Locations

3.1.3 Permitted Sources: TPDES Regulated Stormwater

In 1990, the USEPA developed rules establishing Phase I of the NPDES Stormwater Program, designed to prevent nonpoint source pollutants from being washed by stormwater runoff into municipal separate storm sewer systems and then discharged into local waterbodies (USEPA 2005). Phase I of the program required medium and large permitted dischargers (those generally serving populations of 100,000 or greater) to implement a stormwater management program as a means to control polluted discharges. Approved stormwater management programs for medium and large permitted discharges are required to address a variety of water quality-related issues, including roadway runoff management, municipal-owned operations, and hazardous waste treatment.

Phase II of the rule extended coverage of the NPDES Stormwater program in 2000 to certain small MS4s. Small MS4s are defined as any MS4 in an urbanized area as defined by the U.S. Census Bureau that was not already covered by a Phase I NPDES Stormwater Permit. The Phase II MS4 program requires operators of regulated small MS4s to obtain NPDES permits and develop a stormwater management program. Programs are designed to reduce discharges of pollutants to the "maximum extent practicable," protect water quality, and satisfy appropriate water quality requirements of the CWA. Small MS4 stormwater programs must address the following minimum control measures including Public Education and Outreach; Public Participation/Involvement; Illicit Discharge Detection and Elimination; Construction Site Runoff Control; Post- Construction Runoff Control; and Pollution Prevention/Good Housekeeping.

When evaluating pollutant loads originating from stormwater runoff, a critical distinction must be made between stormwater originating from an area under an NPDES/TPDES regulated discharge permit and stormwater originating from areas not under an NPDES/TPDES regulated discharge permit. To characterize pollutant loads from stormwater runoff, it is necessary to segregate stormwater into two categories:

1) permitted stormwater, which is stormwater originating from an NPDES/TPDES-permitted Phase I or Phase II urbanized area; and
2) unregulated stormwater, which is stormwater originating from any area outside an NPDES/TPDES-permitted Phase I or Phase II urbanized area.

Within the Armand Bayou watershed, there are five individual Phase I and Phase II Ms4 programs that are currently permitted by TCEQ. These programs are operated by:

- City of Houston/Harris County (Phase I permit);
- City of Pasadena (Phase II permit);
- City of Webster (Phase II permit);
- City of Deer Park (Phase II permit); and
- City of La Porte (Phase II permit).

The coverage areas for these permits are shown in Figure 3-1. As shown in the figure, a considerable portion of the Study Area is covered under the City of Houston/Harris County MS4 permit (TPDES Permit No. WQ0004685000). The jurisdictional boundary of the Houston MS4 permit is derived from *Urbanized Area Map Results for Texas* which is based on the 2000 U.S. Census and can be found at the USEPA website http://cfpub.epa.gov/npdes/stormwater/

urbanmapresult.cfm?state=TX. Also included on Figure 3-2 are the location of illicit discharges were identified by HCFCD in the watershed (Close, 2013). Some images of illicit discharges that were identified by HCFCD are provided in Figures 3-3 to 3-6.

Shown in Table 3-5 is a summary of the individual watersheds of interest and the percentage of each watershed that is covered by one or more MS4 permits. As demonstrated in the table, all watersheds are covered by MS4 permit with the exception of Big Island Slough (assessment unit 1103E_01), which for which 93% of the watershed is covered by MS4 permits.

Table 3-5: Percentage of Permitted Stormwater in each Watershed

<table>
<tr><th>Segment</th><th>Receiving Stream</th><th>Regulated Entity Name</th><th>TPDES Number</th><th>Total Area (acres)</th><th>Area under MS4 Permit (Acres)</th><th>Percent of Watershed under MS4 Jurisdiction</th></tr>
<tr><td rowspan="2">1113_02</td><td rowspan="2">Armand Bayou Tidal</td><td>City of Houston/ Harris County</td><td>WQ0004685000</td><td rowspan="2">673</td><td rowspan="2">673</td><td rowspan="2">100%</td></tr>
<tr><td>City of Pasadena</td><td>WQ0004524000</td></tr>
<tr><td rowspan="2">1113A_01</td><td rowspan="2">Armand Bayou Above Tidal</td><td>City of Houston/ Harris County</td><td>WQ0004685000</td><td rowspan="2">3688</td><td rowspan="2">3688</td><td rowspan="2">100%</td></tr>
<tr><td>City of Pasadena</td><td>WQ0004524000</td></tr>
<tr><td rowspan="2">1113B_01</td><td rowspan="2">Horsepen Bayou</td><td>City of Houston/ Harris County</td><td>WQ0004685000</td><td rowspan="2">10668</td><td rowspan="2">10668</td><td rowspan="2">100%</td></tr>
<tr><td>City of Pasadena</td><td>WQ0004524000</td></tr>
<tr><td rowspan="2">1113C_01</td><td rowspan="2">Unnamed Tributary to Horsepen Bayou</td><td>City of Houston/ Harris County</td><td>WQ0004685000</td><td rowspan="2">1777</td><td rowspan="2">1777</td><td rowspan="2">100%</td></tr>
<tr><td>City of Webster</td><td>RN105487318</td></tr>
<tr><td rowspan="4">1113D_01</td><td rowspan="4">Willow Springs Bayou</td><td>City of Houston/ Harris County</td><td>WQ0004685000</td><td rowspan="4">4871</td><td rowspan="4">4871</td><td rowspan="4">100%</td></tr>
<tr><td>City of Deer Park</td><td>RN105484307</td></tr>
<tr><td>City of La Porte</td><td>RN105510440</td></tr>
<tr><td>City of Pasadena</td><td>WQ0004524000</td></tr>
<tr><td rowspan="3">1113E_01</td><td rowspan="3">Big Island Slough</td><td>City of Houston/ Harris County</td><td>WQ0004685000</td><td rowspan="3">5106</td><td rowspan="3">4770</td><td rowspan="3">93%</td></tr>
<tr><td>City of La Porte</td><td>RN105510440</td></tr>
<tr><td>City of Pasadena</td><td>WQ0004685000</td></tr>
</table>

Figure 3-3: Example illicit discharge, Armand Bayou Above Tidal

Figure 3-4: Example illicit discharge, Horsepen Bayou Tidal

Figure 3-5: Example illicit discharge, Willow Springs Bayou

Figure 3-6: Example illicit discharge, Big Island Slough

3.1.4 Concentrated Animal Feeding Operations

There are no CAFOs located within the Study Area.

3.2 Unregulated Sources: Stormwater, On-site Sewage Facilities, and Direct Deposition

Unregulated sources (nonpoint sources) include those sources that cannot be identified as entering the waterbody at a specific location. The following section describes possible major unregulated sources contributing bacteria loading within the Study Area.

Nonpoint sources of bacteria can emanate from wildlife, various agricultural activities, and domesticated animals, land application fields, urban runoff, failing on-site sewage facilities (OSSF), and domestic pets. Bacteria associated with urban runoff can emanate from humans, wildlife, livestock, and domestic pets. Based on the ability of warm-blooded animals to harbor and shed human pathogens, the current USEPA policy establishes the position that it is inappropriate to conclude that livestock and wildlife sources present no risk to human health from waterborne pathogens. Consequently, states and authorized tribes should not use broad exemptions from the bacteriological criteria for waters designated for primary contact recreation based on the presumption that high levels of bacteria resulting from non-human fecal contamination present no risk to human health (USEPA 2002). Water quality data collected from streams draining urban communities often show existing concentrations of fecal coliform bacteria at levels greater than a state's instantaneous standards. A study under USEPA's National Urban Runoff Project indicated that the average fecal coliform concentration from 14 watersheds in different areas within the United States was approximately 15,000 /dL in stormwater runoff (USEPA 1983). Based on data such as these, unregulated stormwater have the potential to be a significant source of fecal bacteria.

3.2.1 Wildlife and Unmanaged Animal Contributions

E coli and enterococci bacteria are common inhabitants of the intestines of all warm-blooded animals, including wildlife such as mammals and birds. In developing bacteria

TMDLs, it is important to identify the potential for bacteria contributions from wildlife by watershed. Wildlife can be naturally attracted to riparian corridors of streams and rivers. With direct access to the stream channel, the direct deposition of wildlife waste can be a concentrated source of bacteria loading to a waterbody. *E coli* and enterococci bacteria from wildlife are also deposited onto land surfaces, where it may be washed into nearby streams by rainfall runoff. Typical of coastal watersheds, many avian species frequent the watershed and the riparian corridors, in particular; this is especially true for areas in and around the Armand Bayou Nature Center.

The significant portions of woody wetlands and undeveloped land in the Study Area also provide a habitat for many species of mammals, reptiles, and amphibians. For example, large populations of feral hogs, white tailed deer, nutria, and feral cats are of specific concern in many parts of the watershed.

There are currently insufficient data available to estimate populations and spatial distribution of wildlife and avian species by watershed. Consequently, it is difficult to assess the magnitude of bacteria contributions from wildlife species as a general category. A comprehensive species list is provided in Appendix E that includes 221 species of birds, 22 species of mammals, and 57 species of reptiles and amphibians.

3.2.2 Unregulated Agricultural Activities and Domesticated Animals

There are a number of unregulated agricultural activities that can also be sources of fecal bacteria loading. Agricultural activities of greatest concern are typically those associated with livestock operations (Drapcho and Hubbs 2002). The following are examples of livestock activities that can contribute to bacteria sources:

- Processed livestock manure is often applied to fields as fertilizer, and can contribute to fecal bacteria loading to waterbodies if washed into streams by runoff before incorporation.
- Livestock grazing in pastures deposit manure containing fecal bacteria onto land surfaces. These bacteria may be washed into waterbodies by runoff if inadequate buffers exist between pastures and waterbodies.
- Livestock may have direct access to waterbodies and can provide a concentrated source of fecal bacteria loading directly into streams.

The estimated numbers of selected livestock by watershed were calculated based on the 2007 USDA county agricultural census data (USDA 2007). The county-level estimated livestock populations were distributed among watersheds based on GIS calculations of pasture land per watershed, based on the National Land Cover Database (NOAA 2011). It should be noted that these are planning level livestock are not evenly distributed across counties or constant with time.

As shown in Table 3-6, cattle are estimated to be the most abundant species of livestock in the Study Area. Livestock numbers and their associated bacteria loading are expected to decrease over time as more land is converted from grazing to developed, urban uses in Armand Bayou watershed.

Table 3-6: Livestock and Manure Estimates by Watershed

Type of Animal	1113_02	1113A_01	1113B_01	1113C_01	1113D_01	1113E_01	Total Animals
Cattle and Calves	0	41	291	0	130	69	**531**
Horses and Ponies	0	8	53	0	24	13	**98**
Goats	0	3	21	0	10	5	**39**
Hogs and Pigs	0	1	6	0	2	1	**10**
Sheep and Lambs	0	1	6	0	3	1	**11**
Bison	0	0	0	0	0	0	**0**
Captive Deer	0	1	7	0	3	2	**13**
Donkey	0	1	4	0	2	1	**8**
Rabbits	0	1	4	0	2	1	**8**
Llamas	0	0	2	0	1	0	**3**
Pullets	0	1	4	0	2	1	**8**
Broilers	0	1	8	0	4	2	**15**
Layers	0	6	43	0	19	10	**78**
Turkeys	0	0	2	0	1	1	**4**
Ducks	0	0	4	0	2	1	**7**
Geese	0	0	2	0	1	0	**3**
Other Poultry	0	1	7	0	3	2	**13**
Total Animals	**0**	**66**	**464**	**0**	**207**	**110**	

According to a livestock study conducted by the American Society of Agricultural Engineers (ASAE) and referenced by the USEPA (2000) in their Bacteria Indicator Tool, the daily fecal coliform production rates by livestock species were estimated as follows (ASAE 1998):

- Beef cattle release approximately 1.04E+11 per animal per day
- Dairy cattle release approximately 1.01E+11 per animal per day
- Swine release approximately 1.08E+10 per animal per day
- Chickens release approximately 1.36E+08 per animal per day
- Sheep release approximately 1.20E+10 per animal per day
- Horses release approximately 4.20E+08 per animal per day
- Turkey release approximately 9.30E+07 per animal per day
- Ducks release approximately 2.43E+09 per animal per day
- Geese release approximately 4.90E+10 per animal per day

Using the estimated livestock populations and the fecal coliform production rates from ASAE, an estimate of fecal coliform production from each group of livestock was calculated in

Table 3-7 for each watershed of the Study Area. It should be noted that only a fraction of these fecal coliform loading estimates are expected to reach the receiving water, either washed into streams by runoff or by direct deposition from wading animals. Cattle appear to represent the most significant livestock source of fecal bacteria based on overall loading estimates.

Table 3-7: Fecal Coliform Production Estimates for Selected Livestock (x10^9 /day)

Stream Name	Cattle & Calves	Horses & Ponies	Sheep & Lambs	Hogs & Pigs	Ducks	Geese	Chickens	Total
Armand Bayou Tidal	2,138	2	5	4	1	6	1	2,156
Armand Bayou Above Tidal	11,717	9	28	23	3	32	3	11,816
Horsepen Bayou	33,890	25	81	67	10	93	10	34,176
Unnamed Tributary to Horsepen Bayou	5,646	4	14	11	2	16	2	5,693
Willow Springs Bayou	15,474	11	37	30	4	43	4	15,604
Big Island Slough	16,222	12	39	32	5	45	5	16,359

3.2.3 Failing On-site Sewage Facilities

On-site sewage facilities (OSSFs) can be a source of bacteria loading to streams and rivers. Bacteria loading from failing OSSFs can be transported to streams in a variety of ways, including runoff from surface ponding or through groundwater. Indicator bacteria-contaminated groundwater can also be discharged to creeks through springs and seeps.

Over time, most OSSFs operating at full capacity will fail if not properly maintained. OSSF failures are proportional to the adequacy of a state’s minimum design criteria (Hall 2002). The 1995 American Housing Survey conducted by the U.S. Census Bureau estimates that, nationwide, 10 percent of occupied homes with OSSFs experience malfunctions during the year (U.S. Census Bureau 1995). A statewide study conducted by Reed, Stowe & Yanke, LLC (2001) reported that approximately 12 percent of the OSSFs in Harris County were chronically malfunctioning. Most studies estimate that the minimum lot size necessary to ensure against contamination is roughly one-half to one acre (Hall 2002). Some studies, however, found that lot sizes in this range or even larger could still cause contamination of ground or surface water (University of Florida 1987). It is estimated that areas with more than 40 OSSFs per square mile (6.25 septic systems per 100 acres) can be considered to have potential contamination problems (Canter and Knox 1985).

Only permitted OSSF systems are recorded by authorized county or city agents; therefore, it is difficult to estimate the exact number of OSSFs in use in the Study Area. Table 3-8 lists the OSSF totals based on GIS data information provided by H-GAC. Figure 3-3 displays unsewered areas that do not fall under the wastewater service areas and may be expected to have septic systems serving households in these areas.

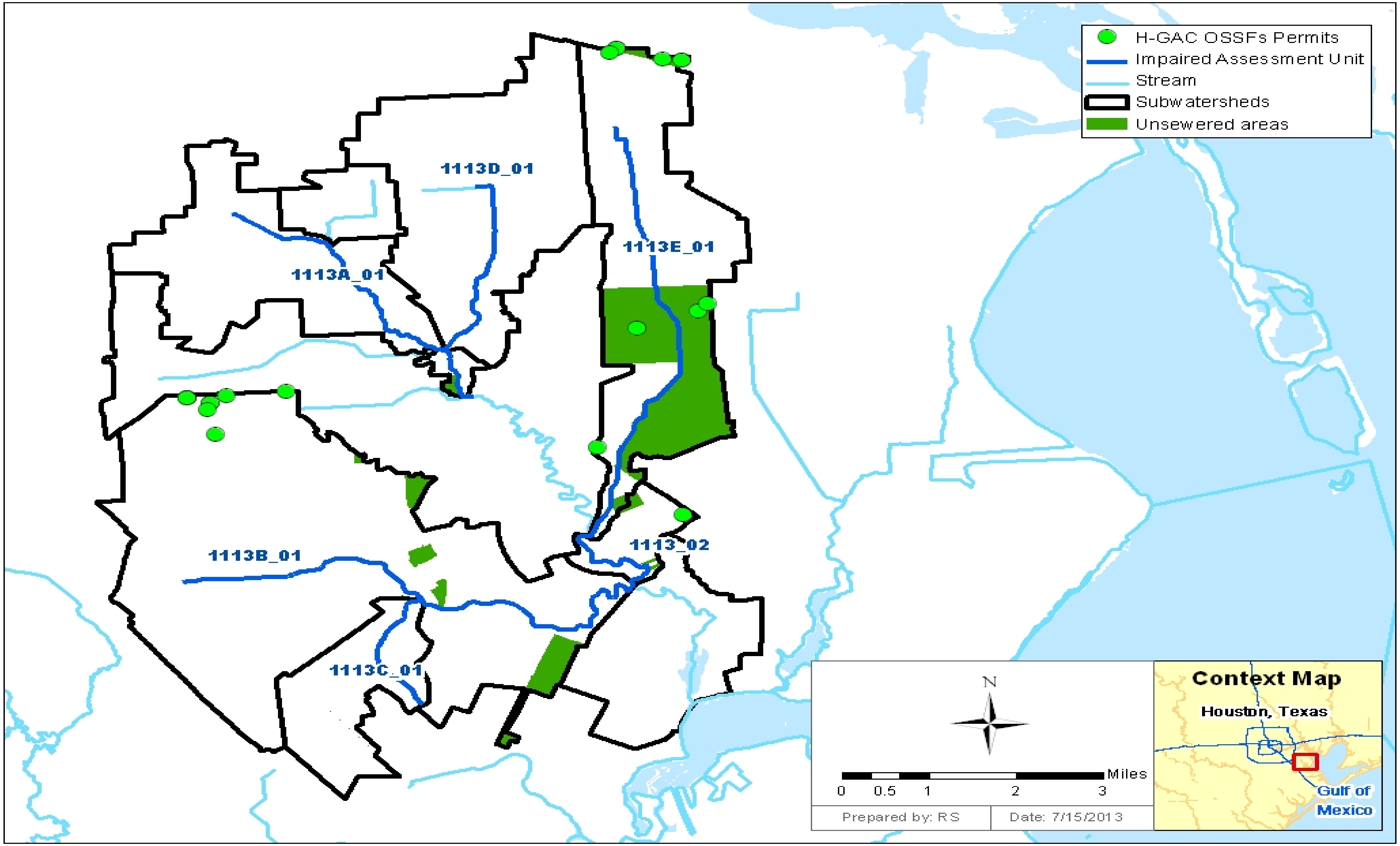

Figure 3-7: Unsewered Areas and Subdivisions with OSSF

For the purpose of estimating fecal coliform loading in watersheds, the OSSF failure rate of 12 percent from the Reed, Stowe & Yanke, LLC (2001) report for Texas Region 4 was used. Using this 12 percent failure rate, calculations were made to characterize fecal coliform loads in each watershed.

Fecal coliform loads were estimated using the following equation (USEPA 2001):

$$\#\frac{counts}{day} = (\#Failing\_systems) \times \left(\frac{10^6 counts}{100ml}\right) \times \left(\frac{70gal}{personday}\right) \times \left(\#\frac{person}{household}\right) \times \left(3785.2\frac{ml}{gal}\right)$$

The average of number of people per household was calculated to be 2.77 for the Study Area (U.S. Census Bureau 2010) based on an average household density for Houston, La Porte, Deer Park, Pasadena. Approximately 70 gallons of wastewater were estimated to be produced on average per person per day (Metcalf and Eddy 1991). The fecal coliform concentration in failing septic tank effluent was estimated to be 10^6 per 100 mL of effluent based on reported concentrations from a number of published reports (Metcalf and Eddy 1991; Canter and Knox 1985; Cogger and Carlile 1984). Using this information, the estimated load from failing septic systems within each subwatershed was calculated and is summarized in Table 3-8. Based on this data, it was determined that the estimated fecal coliform loading from OSSFs in the Study Area were found to be negligible.

Table 3-8: Estimated Number of OSSFs per Watershed and Fecal Coliform Load

Segment	Stream Name	OSSF data from H-GAC	# of Failing OSSFs	Estimated Loads from OSSFs (x 10^9 counts/day)
1113_02	Armand Bayou Tidal	1	0.12	0.88
1113A_01	Armand Bayou Above Tidal	0	0	0
1113B_01	Horsepen Bayou	9	1.08	7.94
1113C_01	Unnamed Tributary to Horsepen Bayou	0	0	0
1113D_01	Willow Springs Bayou	0	0	0
1113E_01	Big Island Slough	10	1.2	8.82

3.2.4 Domestic Pets

Fecal matter from dogs and cats is transported to streams by runoff from urban and suburban areas and can be a potential source of bacteria loading. On average nationally, there are 0.58 dogs per household and 0.66 cats per household (American Veterinary Medical Association 2002). Using the U.S. Census data at the block level (U.S. Census Bureau 2010), dog and cat populations can be estimated for each watershed. Table 3-9 summarizes the estimated number of dogs and cats for the watersheds of the Study Area.

Table 3-9: Estimated Numbers of Pets

Segment	Stream Name	Dogs	Cats
1113_02	Armand Bayou Tidal	120	137
1113A_01	Armand Bayou Above Tidal	3,061	3,483
1113B_01	Horsepen Bayou	6,424	7,310
1113C_01	Unnamed Tributary to Horsepen Bayou	4,664	5,307
1113D_01	Willow Springs Bayou	4,735	5,388
1113E_01	Big Island Slough	3,003	3,417

Table 3-10 provides an estimate of the fecal coliform load from pets. These estimates are based on estimated fecal coliform production rates of $5.4x10^8$ per day for cats and $3.3x10^9$ per day for dogs (Schueler 2000). Only a small portion of these loads is expected to reach waterbodies, through wash-off of land surfaces and conveyance in runoff.

Table 3-10: Fecal Coliform Daily Production by Pets (x 10^9)

Segment	Stream Name	Dogs	Cats	Total Load (cfu/day x 10^9)
1113_02	Armand Bayou Tidal	396	74	470
1113A_01	Armand Bayou Above Tidal	10,101	1,881	11,982
1113B_01	Horsepen Bayou	21,200	3,948	25,148
1113C_01	Unnamed Tributary to Horsepen Bayou	15,391	2,866	18,257
1113D_01	Willow Springs Bayou	15,624	2,909	18,533
1113E_01	Big Island Slough	9,909	1,845	11,754

3.2.5 Bacteria Re-growth and Die-off

Bacteria are living organisms that grow and die. Certain enteric bacteria can regrow in organic materials if appropriate conditions prevail (*e.g.*, warm temperature). It has been shown that fecal organisms can regrow from improperly treated effluent during their transport in pipe networks, and they can regrow in organic rich materials such as compost and sludges. While the die-off of indicator bacteria has been demonstrated in natural water systems due to the presence of sunlight and predators, the potential for their regrowth is less well understood. Both processes (regrowth and die-off) are in-stream processes and are not considered in the bacteria source loading estimates of each water body.

CHAPTER 4
TECHNICAL APPROACH AND METHODS

The TMDL represents the maximum amount of a pollutant that the stream can receive in a single day without exceeding the water quality standard. A TMDL is expressed as the sum of three elements as described in the following mathematical equation:

$$TMDL = \Sigma WLA + \Sigma LA + MOS$$

The wasteload allocation (WLA) is the portion of the TMDL allocated to existing and future permitted (point) sources. The load allocation (LA) is the portion of the TMDL allocated to unregulated (nonpoint) sources, including natural background sources. The MOS is intended to account for uncertainty and ensure that standard for contact recreation will be met. Thus, the allowable pollutant load that can be allocated to point and nonpoint sources can then be defined as the TMDL minus the MOS.

40 CFR §130.2(1), states that TMDLs can be expressed in terms of mass per time, toxicity, or other appropriate measures. For *E coli* or enterococci bacteria, TMDLs are expressed as numbers per day, where possible, or as a percent reduction goal, and represent the maximum one day load the stream can assimilate while still attaining the standard for contact recreation. For the Armand Bayou Watershed, to quantify allowable pollutant loads, percent reduction goals to achieve standard for contact recreation, and specific TMDL allocations for point and nonpoint sources, two different methods are used: 1) the load duration curve method for non-tidal streams and 2) a mass balance method using a tidal prism for tidal streams. These two different technical approaches are described in this Section.

4.1 Using Load Duration Curves to Develop TMDLs

The TMDL calculations for freshwater streams presented in this report are derived from LDCs. LDCs facilitate development of TMDLs, and as a TMDL development tool, can be effective at identifying whether impairments are associated with point or nonpoint sources. The technical approach for using LDCs for TMDL development includes the four following steps described in Subsections 4.2 through 4.4 below:

1. Preparing flow duration curves (FDC) for gaged and ungaged WQM stations;
2. Estimating existing bacteria loading in the receiving water using ambient water quality data;
3. Using LDCs to identify the critical condition that will dictate loading reductions necessary to attain the contact recreation standard; and
4. Interpreting LDCs to derive TMDL elements – WLA, LA, MOS, and percent reduction goal.

Historically, in developing WLAs for pollutants from point sources, it was customary to designate a critical low flow condition (*e.g.*, 7Q2) at which the maximum permissible loading was calculated. As water quality management efforts expanded in scope to quantitatively address nonpoint sources of pollution and types of pollutants, it became clear that this single critical low flow condition was inadequate to ensure suitable water quality across a range of flow conditions. Because the LDC covers a range of flow conditions, use of the LDC obviates the need to determine a design storm or selected flow recurrence interval with which to characterize the appropriate flow level for the assessment of critical conditions. For waterbodies impacted by both point and nonpoint sources, the “nonpoint source critical condition” would typically occur during high flows, when rainfall runoff would contribute the bulk of the pollutant load, while the “point source critical condition” would typically occur during low flows, when WWTF effluent would dominate the base flow of the impaired water.

LDCs display the maximum allowable load over the complete range of flow conditions by a line using the calculation of flow multiplied by the water quality criterion. Using LDCs, a TMDL can be expressed as a continuous function of flow, or as a discrete value derived from a specific flow condition.

4.2 Development of Flow Duration Curves

Flow duration curves serve as the foundation of LDCs and are graphical representations of the flow characteristics of a stream at a given site. When historical flow data are available, FDCs utilize the hydrologic record from stream gages to forecast future recurrence frequencies. While many WQM stations throughout Texas do not have long term flow data, there are various methods that can be used to estimate flow frequencies at ungaged stations or gaged stations missing flow data.

The most basic method to estimate flows at an ungaged site involves 1) identifying an upstream or downstream flow gage; 2) calculating the contributing drainage areas of the ungaged sites and the flow gage; and 3) calculating daily flows at the ungaged site by using the flow from an acceptable nearby gaged site multiplied by the drainage area ratio. Because no upstream/downstream gages were located on Armand Bayou, a more complex approach was used that correlates nearby gages and also considers watershed differences in pervious and impervious cover, land cover, WWTF discharges, and the hydrologic properties of the watershed. A more detailed explanation of the methods for estimating flow at ungaged WQM stations is provided in Appendix F.

Flow duration curves are a type of cumulative distribution function. The flow duration curve represents the fraction of flow observations that exceed a given flow at the site of interest. The observed flow values are first ranked from highest to lowest then, for each observation, the percentage of observations exceeding that flow is calculated. The flow value is read from the y-axis, which is typically on a logarithmic scale since the high flows would otherwise overwhelm the low flows. The flow exceedance frequency is read from the x-axis, which is numbered from 0 to 100 percent, and may or may not be logarithmic. The lowest measured flow occurs at an exceedance frequency of 100 percent indicating that flow has equaled or exceeded this value 100 percent of the time, while the highest measured flow is found at an exceedance frequency of 0 percent. The median flow occurs at a flow exceedance frequency of 50 percent.

While the number of observations required to develop a flow duration curve is not rigorously specified, a flow duration curve is usually based on more than 5-years of observations, and encompasses inter-annual and seasonal variation. Ideally, the drought of record and flood of record are included in the observations. For this purpose, the long-term flow gaging stations operated by the USGS are utilized. As previously mentioned, there are no long-term flow data from within the Study Area and therefore, flows were estimated for all WQM stations/watersheds in Armand Bayou using the gage correlation approach described in Appendix F. Two USGS gages outside the watershed, Sims Bayou at Hiram Clarke Street and Vince Bayou at Pasadena, TX, were chosen to conduct flow projections. The period of record for flow data used from this station was 2000 through 2013.

A typical semi-log flow duration curve exhibits a sigmoidal shape, bending upward near a flow exceedance frequency value of 0 percent and downward at a frequency near 100 percent, often with a relatively constant slope in between. For sites that on occasion exhibit no flow, the curve will intersect the abscissa at a frequency less than 100 percent. As the number of observations at a site increases, the line of the FDC tends to appear smoother. However, at extreme low and high flow values, flow duration curves may exhibit a "stair step" effect due to the USGS flow data rounding conventions near the limits of quantitation.

FDCs can be subdivided into hydrologic condition classes to facilitate the diagnostic and analytical uses of flow and LDCs. The hydrologic classification scheme utilized in this application is described in Table 4-1.

Table 4-1: Hydrologic Classification Scheme

Flow Exceedance Percentile	Hydrologic Condition Class
0-20	Highest flows
20-80	Mid-range flows
80-100	Lowest flows

Figures 4-1 through 4-4 presents the FDC developed for the downstream WQM station in Armand Bayou Above Tidal (Figure 4-1); Unnamed Tributary to Horsepen Bayou (Figure 4-2); Willow Springs Bayou (Figure 4-3) and Big Island Slough (Figure 4-4) for calculating the TMDL of the 303(d) listed freshwater stream using the gage correlation method outlined above and further described in Appendix F. The flow exceedance percentiles for these segments are presented in tabular form in Appendix F.

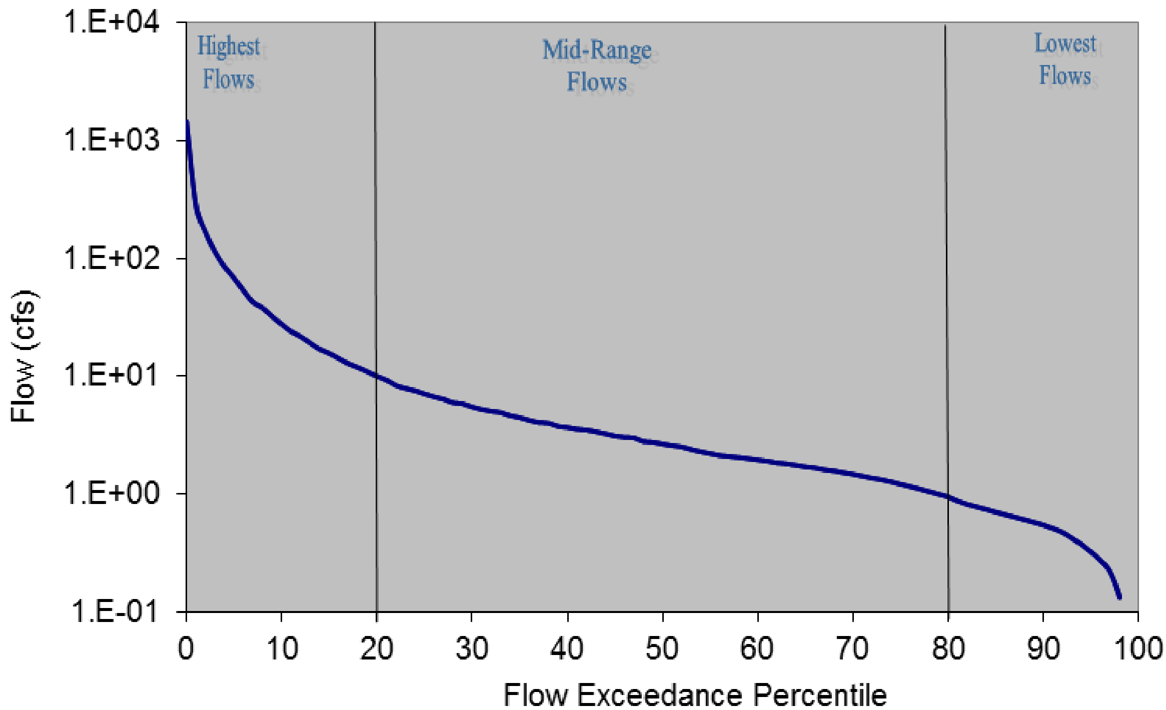

Figure 4-1: Flow Duration Curve for Armand Bayou Above Tidal (1113A_01)

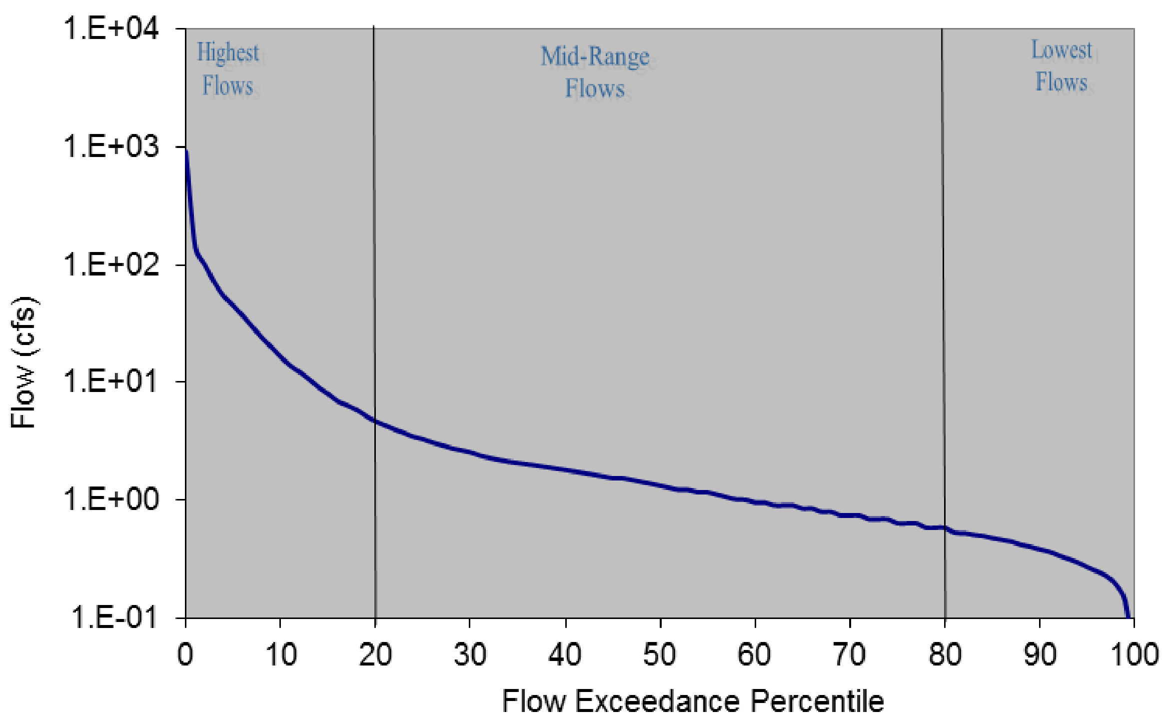

Figure 4-2: Flow Duration Curve for Unnamed Tributary to Horsepen Bayou (1113C_01)

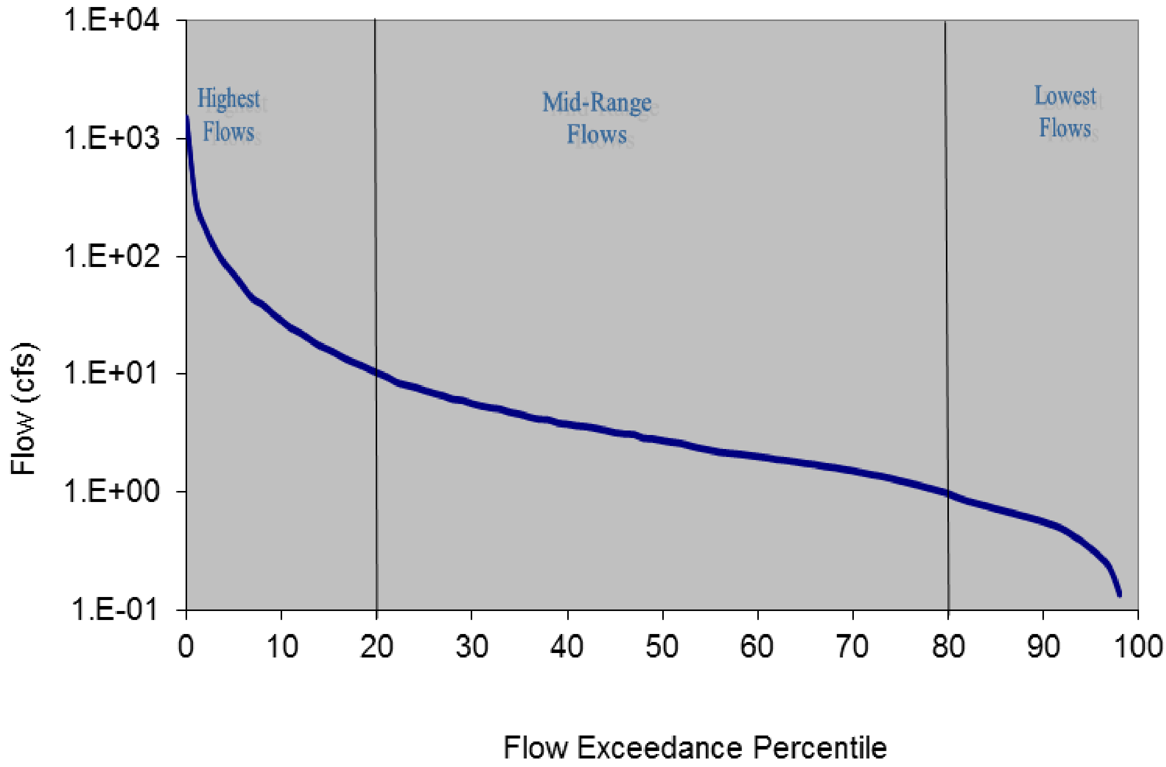

Figure 4-3: Flow Duration Curve for Willow Springs Bayou (1113D_01)

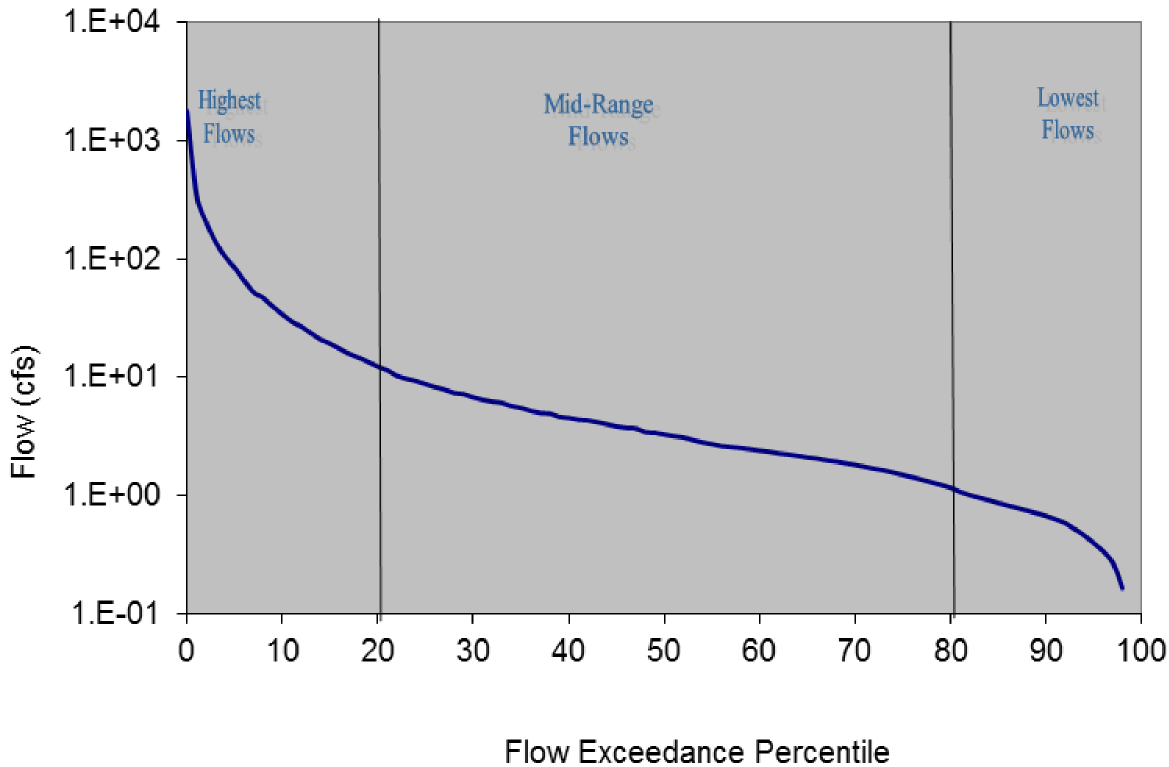

Figure 4-4: Flow Duration Curve for Big Island Slough (1113E_01)

4.3 Estimating Current Point and Nonpoint Loading and Identifying Critical Conditions from Load Duration Curves

Another key step in the use of LDCs for TMDL development is the estimation of existing bacteria loading from point and nonpoint sources and the display of this loading in relation to the TMDL. There were no domestic or otherwise continuously discharging point sources (i.e., WWTFs) in the above tidal watersheds. Therefore, the TMDL was allocated between stromwater wasteload allocation and the load allocation based on the percentage of the watershed covered by MS4 permits

The critical condition for the load duration curve is considered the flow regime that requires the most significant bacteria reduction to meet water quality standards. For all watersheds of interest, this was the high flow (0-20th percentile flow) conditions.

4.4 Development of Bacteria TMDLs for Freshwater Streams Using Load Duration Curves

The final step of the process involves developing calculations to support development of the TMDL allocations.

Step 1: Generate Bacteria LDCs. LDCs are similar in appearance to flow duration curves; however, the ordinate is expressed in terms of a bacteria load in counts/day. The curve represents the water quality criteria for *E coli* (either single sample criteria of 394 MPN/dL or geometric mean criteria of 126 MPN/dL), expressed in terms of a load through multiplication by the continuum of flows at the site determined using the gage correlation approach. The basic steps to generating an LDC involve:

- develop flow estimates using the gage correlation approach described in Appendix F and develop flow duration curve as described in previous sections;
- obtaining the water quality data for the WQM station;
- matching the water quality observations with the flow estimates from the same date;
- display a curve on a plot that represents the allowable load multiply the actual or estimated flow by the surface water quality standard for each respective indicator;
- multiplying the flow by the water quality parameter concentration to calculate daily loads; then
- plotting the flow exceedance percentiles and the daily observed bacteria load .

The culmination of these steps is expressed in the following formula, which is displayed on the LDC as the TMDL curve:

*TMDL (counts/day) = criterion * flow (cfs) * unit conversion factor*

Where: criterion = 399 counts/dL (E coli) and

*unit conversion factor = 24,465,755 dL/ft3 * seconds/day*

The flow exceedance frequency (x-value of each point) is obtained by looking up the historical exceedance frequency of the measured or estimated flow; in other words, the percent of historical observations that equal or exceed the measured or estimated flow. Historical observations of bacteria concentration are paired with flow data and are plotted on the LDC.

The indicator bacteria load (or the y-value of each point) is calculated by multiplying the indicator bacteria concentration (counts/dL) by the instantaneous flow (cubic feet per second [cfs]) at the same site and time, with appropriate volumetric and time unit conversions. Indicator bacteria loads representing exceedance of water quality criterion fall above the water quality criterion line.

Figure 4-5 provides a schematic representation of where permitted and unregulated sources of pollution occur throughout the entire hydrograph for a typical stream. This figure shows that runoff typically contributes pollutant loads during high flow to mid-ranged flow conditions. However, flows do not always correspond directly to runoff events. For instance, high flows may occur in dry weather and runoff influence may be observed with low or moderate flows.

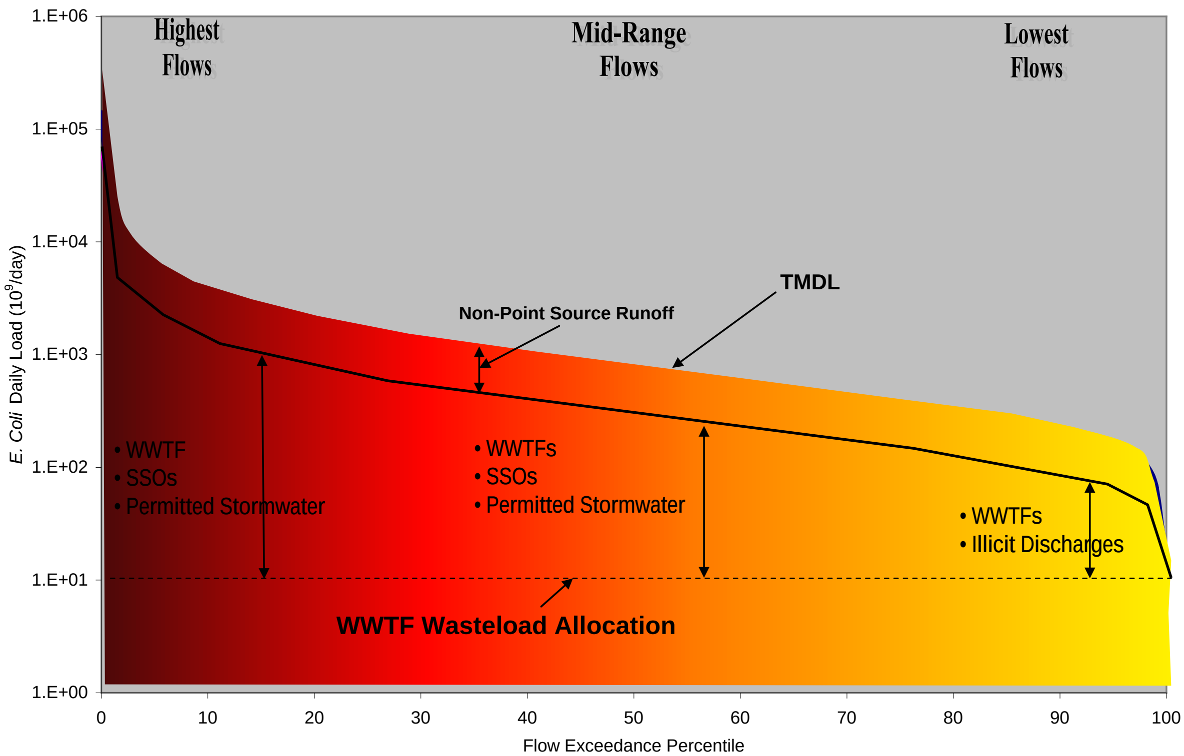

Figure 4-5: Schematic Diagram – Interpreting Sources and Loads

Step 2: Develop LDCs with MOS. The MOS may be defined explicitly or implicitly. An LDC depicting slightly lower estimates than the TMDL is typically developed to incorporate an MOS into the TMDL calculations. A typical explicit approach would reserve some fraction of the TMDL (*e.g.,* 5%) as the MOS. For the TMDLs for freshwater streams in this report, an explicit MOS of 5 percent of the TMDL value (5% of the geometric mean water quality criterion) has been selected. The MOS at any given percent flow exceedance, therefore, is defined as the difference in loading between the TMDL and the TMDL with MOS.

Step 3: Calculate WLA. As previously stated, the pollutant load allocation for permitted (point) sources is defined by the WLA. A point source can be either a wastewater or stormwater permitted discharge. Stormwater point sources are typically associated with urban and industrialized areas, and recent USEPA guidance includes NPDES-permitted stormwater discharges as point source discharges and, therefore, part of the WLA.

The LDC approach recognizes that the assimilative capacity of a waterbody depends on the flow, and that maximum allowable loading will vary with flow condition. TMDLs can be expressed in terms of maximum allowable concentrations, or as different maximum loads allowable under different flow conditions, rather than single maximum load values. This concentration-based approach meets the requirements of 40 CFR, 130.2(i) for expressing TMDLs “in terms of mass per time, toxicity, or other appropriate measures” and is consistent with USEPA’s Protocol for Developing Pathogen TMDLs (USEPA 2001).

WLA for WWTF. WLAs may be set to zero for watersheds with no existing or planned permitted point sources. For watersheds with permitted point sources, WLAs may be derived from TPDES permit limits. In this report, there were no WWTFs in the freshwater segments. Therefore, no WLAs were established for WWTFs.

WLA for NPDES/TPDES MS4s. Given the lack of data and the complexity of quantifying bacteria concentrations or loads associated with wet weather events, the percentage of a watershed that is under MS4 jurisdiction is used to estimate the load that should be allocated as the permitted stormwater load. For example, the area of the City of Houston/Harris County and City of Pasadena permitted MS4 discharges in the project area is estimated to be 10,668 acres, 100 percent of the Horsepen Bayou (Segment 1113B_01) watershed. Therefore, 100 percent of the wasteload allocation will be designated as the WLA for stormwater.

Step 4: Calculate LA. LAs for unregulated sources (nonpoint sources) can be calculated under different flow conditions as the water quality target load minus the sum of WLA for WWTFs (if any) and permitted stormwater (or MS4). The LA at any particular flow exceedance is calculated as shown in the equation below.

$$LA = TMDL - MOS - \Sigma WLA_{WWTF} - \Sigma WLA_{MS4}$$

Where:

LA = allowable load from unregulated sources
TMDL= total allowable load
ΣWLA_{WWTF} = sum of all WWTF loads
ΣWLA_{MS4} = sum of all MS4 loads
MOS = margin of safety

Step 5: Estimate WLA Load Reduction. If there were WWTFs in the segments of interest for this report, the WLA load reduction for TPDES-permitted WWTFs would not be calculated. Instead, it would be assumed that continuous dischargers are adequately regulated under existing permits and, therefore, no WLA reduction would be required. However, for permitted stormwater the load reduction will be the same as the percent reduction goal established for the LA (nonpoint sources).

Step 6: Estimate LA Load Reduction. A percent reduction goal is derived for each WQM station on each segment for the geometric mean criterion. The goal is determined by comparing the TMDL for each of the three flow regimes with the observed geometric mean load for the flow regime.

Percent Reduction Goal = ABS(Geometric Mean of Indicator Bacteria Load – TMDL) / Geometric Mean of Indicator Bacteria Load

4.5 Development of Bacteria TMDLs for Tidal Streams Using a Mass Balance Approach

4.5.1 Modeling Approach

A time-variable tidal prism modeling approach with a moderate level of spatial resolution was used to simulate the bacterial indicator loads and establish TMDLs for the tidal segments of the Study Area. The tidal prism is the volume of water gained in a tidal stream between low and high tide levels. In addition, the model included from 1/1/2010 to 12/31/2012. Load calculations were developed for a series of reaches within Armand Bayou Tidal as well as the portions of the major tributaries discharging to Armand Bayou Tidal that periodically are influenced by tidal fluctuations. The model incorporates the three primary mechanisms through which Enterococci loadings and water enter the impaired systems: i) rain-induced freshwater inputs via tributaries or direct runoff, ii) direct point source discharges, and iii) tidally influenced loadings, which are introduced during the diurnal tidal fluctuations that occur in the system. The model assumes that Enterococci are removed with the net estuarine flow from the system and via net decay. A generalized schematic of the source and sink terms for the tidally influenced impaired waterbodies is presented in Figure 4-3.

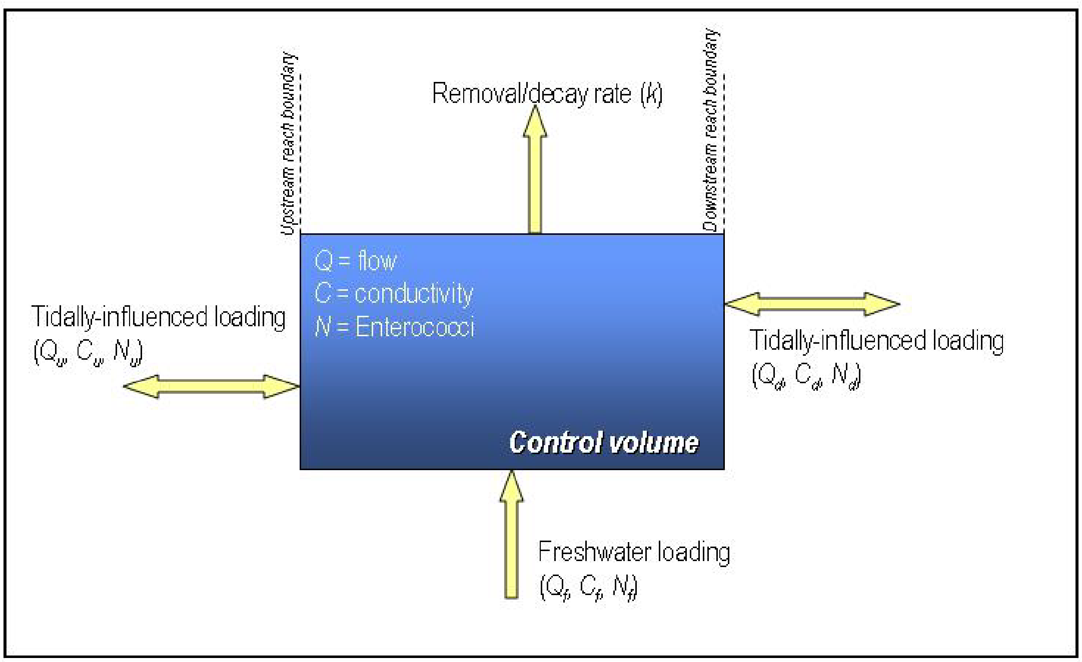

Figure 4-3 Conceptual Model for Sources and Sinks of Enterococci

The mass balance of water for a given reach at a given time step can be written as follows:

$$\frac{dV}{dt} = Q_u + Q_f - Q_d \qquad (1)$$

Where: Q_u = volume of water crossing the upstream boundary of the reach [m^3/hr]

Q_d = volume of mixed water crossing the downstream boundary of the reach [m^3/hr]

Q_f = volume of freshwater inflow (runoff, tributaries, and WWTFs) discharging along the reach [m^3/hr],

dV/dt = change in volume of the reach with time [m^3/hr]

The following paragraphs summarize the steps that were followed to complete the tidal prism model.

Step 1: Define Reaches.

Tidal, Segment 1113_02, was kept as one reach due to its small size and Horsepen Bayou, Segment 1113B was divided into five reaches (Figure 4-4). The tidal prism model includes tributaries discharging to Armand or Horsepen Bayous including Big Island Slough, Armand Bayou Above Tidal, Willow Springs Bayou, and Unnamed Tributary to Horsepen Bayou

Data from TSARP models were used to calculate cross-sectional areas for the boundaries of each main stem reach. Cross-sectional areas for small tributaries were estimated using DEM (Digital Elevation Model) profile graphspublished in 2009 provided by USGS. Cross-section data for the two streams included in the Study Area are provided in electronic format in Appendix G..

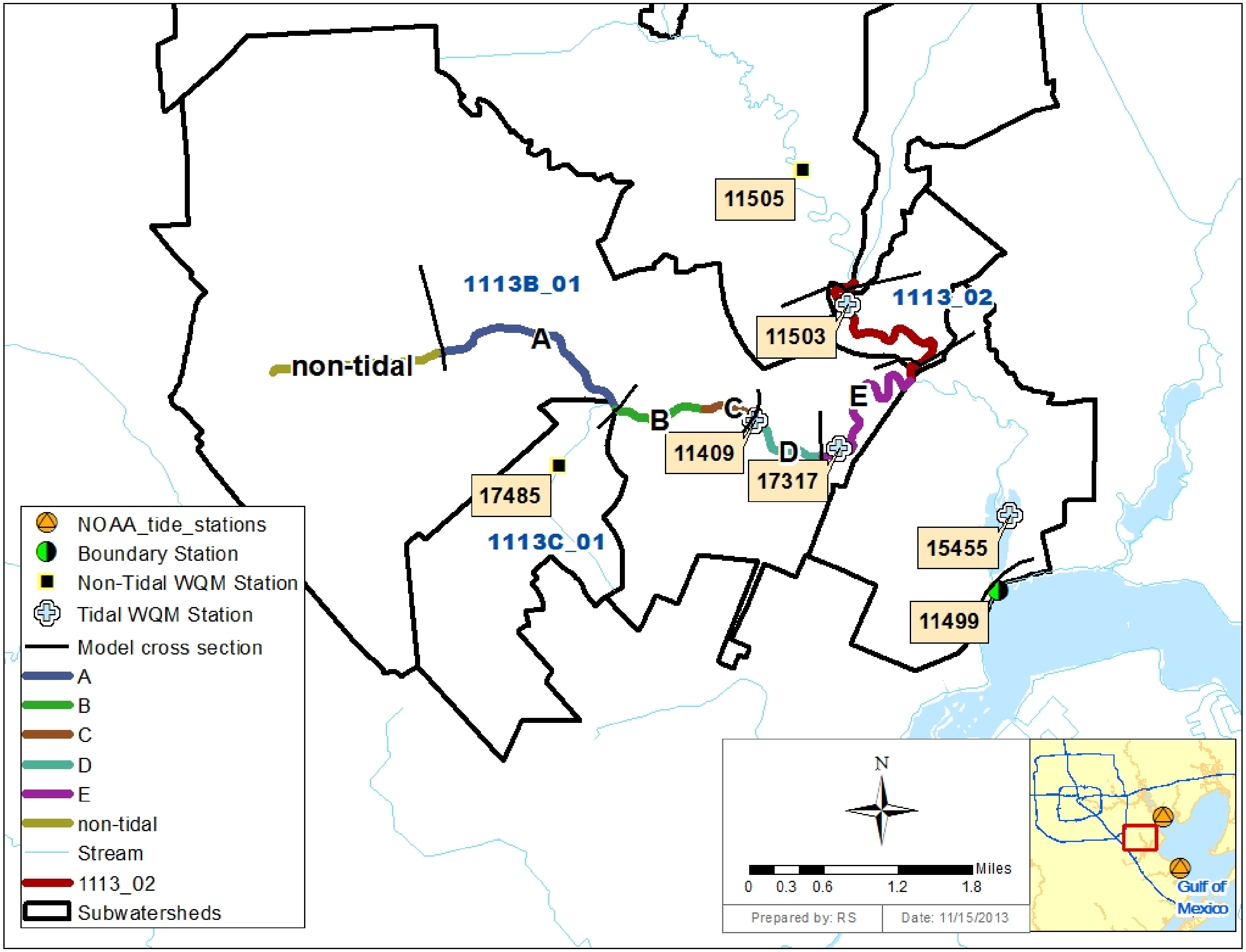

Figure 4-4 Schematic of the Modified Tidal Prism Model

Step 2: Establishing Tributary Inflows and Loads

The model requires time series for inflow and bacterial indicator loads from the freshwater tributaries (the model headwaters) discharging to the tidal portions. The methods for estimating these headwater boundary flows and Enterococci loads are summarized in this step.

Inflows from Non-Tidal Tributaries to Tidal Model Reaches

Estimated daily inflows from non-tidal (freshwater) tributary streams to the tidal model reaches were derived from the drainage area ratio method described in Appendix F. These daily inflows were then disaggregated to hourly time series for the modeled period (2010 through 2012), and provided in Appendix H in electronic format.

Enterococci Loads from Upstream Freshwater Segments

Indicator bacteria concentrations measured at the most downstream WQM stations on non-tidal tributaries, including Unnamed Tributary to Horsepen Bayou (17485) and Armand Bayou (11505) were used to estimate Enterococci loads to the tidal prism model. For most of the WQM stations on these tributaries, only *E. coli* or fecal coliform data were available. Therefore, Enterococci concentrations were estimated from *E. coli* or fecal coliform data using Enterococci/*E. coli* (ENT/EC) or Enterococci/fecal coliform (ENT/FC) conversion ratios, based on data collected by the City of Houston and H-GAC for their Alternate Indicator Study (Running 2007). The median ENT/EC and ENT/FC ratios were 0.34 and 0.27, respectively. For dates with no historical water quality data available, the geometric mean of the observed values of each respective station was used. For tributaries with no WQM stations, Enterococci loads estimated from the ratio of event mean concentrations (EMC) of tributaries with WQM stations. Tributary load input datasets for Enterococci are included in electronic format in Appendix H and summarized in Table 4-2.

Table 4-2 Summary of Tributary Inflows and Loads to the Tidal Prism Model

Interface	Average Flow (m^3/day)	Average Flow (cfs)	Average Enterococci Load (counts/day)
Armand Bayou Above Tidal	1.12E+04	4.58E+00	8.77E+08
Tributary 1 (to Reach A)	4.98E+03	2.04E+00	2.57E+09
Tributary 2 (to Reach B)	2.85E+03	1.17E+00	2.09E+09
Tributary 3 (to Reach C)	1.47E+03	6.02E-01	1.08E+09
Tributary 4 (to Reach C)	1.82E+03	7.43E-01	1.32E+09

Step 3: Estimating Direct (non-tributary) Point and Nonpoint Source InFlows and Loading to the System.

The key variables required for estimating loading into the model reaches are direct runoff to the tidal streams modeled, WWTF discharges to the various reaches, and indicator bacteria concentrations in runoff and WWTF effluents. The methods for estimating these tidal prism inputs are summarized below.

Permitted Sources: Continuous Point Source Dischargers (WWTFs)

Two TPDES-permitted WWTFs that continuously discharge wastewater are located in the Horsepen Bayou Watershed. To be consistent with estimating bacterial indicator loads under the LDC method, average monthly flows from DMRs were again used to estimate fecal coliform and Enterococci loads from discrete point sources as inputs to the tidal prism model. Loads were calculated using maximum monthly geometric mean data for Enterococci when available from TCEQ, and converted from fecal coliform to Enterococci loads using the 0.27 ENT/FC ratio). Since no bacteria data were available for facility 10495-152, Enterococci loads were calculated from the ratio of permitted flow from facility 10539-001. A summary of these data are shown in Table 4-3.

Table 4-3 Summary of Existing WWTF Loads in Model

Model Reach	TPDES Permit Number	Flow (average self-reported) m^3/hr	Flow (average self-reported) MGD	Enterococci Concentration (counts/dL)	Enterococci Load (counts/day)
A	10495-152	5.06E+03	1.44	13[b]	6.0E+08
E	10539-001	1.99E+04	5.58	25[a]	5.0E+09

[a] *Maximum value of monthly self-reported geomeans (estimated from 0.27 ENT/FC ratio before 11/20/2009)*
[b] *Estimated from facility 10539-001*

Permitted and Unregulated Stormwater Runoff

Runoff from each of the watersheds was defined using the Harris County Flood Control District (HCFCD) Hydrologyic Modeling System (HMS) flow simulation model. The HCFCD model was updated to include hourly rainfall from HCOEM Rainfall Gage 250 located at the downstream boundary of 1113B Horsepen Bayou Reach C.

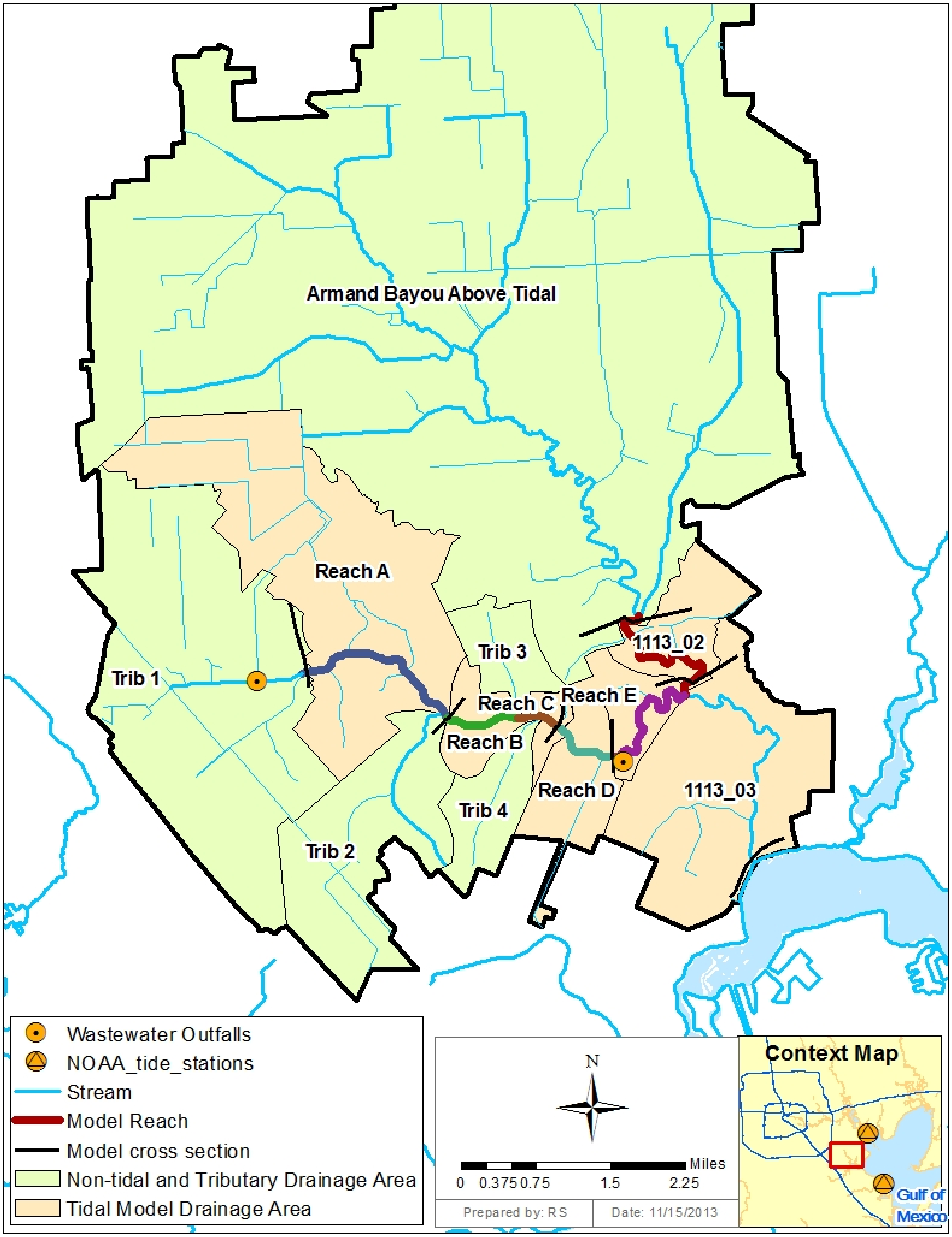

Figure 4-5 Drainage Areas for the Tidal Prism Model Reaches

Event mean concentrations (EMC) for Enterococci were estimated based on fecal coliform EMCs obtained from the Stormwater Management Joint Task Force in 2002. The ENT/FC ratio (0.27) was applied to obtain Enterococci EMCs for different land cover categories. The Enterococci concentrations used for the tidal prism model are included in Table 4-4.

Table 4-4 EMCs for the Armand Bayou Watershed

Land Cover Description	Enterococci EMCs (cfu/dL)
Developed	18,000
Cultivated Land	700
Grassland/Herbaceous	700
Pasture/Hay	700
Woodland	400
Open Water	0
Wetlands	0
Transitional/Bare	12,000

Average stormwater runoff loads from the contributing subwatershed of each reach are summarized in Table 4-5. Runoff flow and Enterococci load calculations are provided in electronic format in Appendix I.

Table 4-5 Stormwater Runoff Loads to the Tidal Prism Model

Reach	Average Flow (m^3/day)	Average Flow (cfs)	Average Enterococci Load (counts/day)
1113B A	1.64E+03	6.72E+00	7.10E+11
1113B B	3.06E+03	1.25E+00	1.15E+11
1113B C	1.27E+03	5.20E-01	6.27E+10
1113B D	1.10E+03	1.10E+00	8.44E+10
1113B E	2.89E+03	1.18E+00	5.77E+10
1113_02	1.47E+04	6.02E*00	9.59E+10

Note: Variable daily loads were input into the model. The loads presented here are the averages over the simulation period (01/01/2010 to 12/31/2012).

Step 4: Estimate Tidal Flows. Tidal flows for each reach were computed as the tidal exchange over the course of one hour, and were estimated as the difference in volume between two consecutive time steps (Equation 1). To calculate volumes, one hour gage data for the period of 01/01/2010 – 12/31/2012 were downloaded from the Texas Coastal Ocean Observation Network Station 507 at Eagle Point (http://www.cbi.tamucc.edu/obs/507. After adjusting cross-sectional areas to reflect tidal elevation, the hourly volumes for each reach were calculated as the average of the cross-sectional areas at the downstream and upstream reach boundaries times the length of the reach.

Step 5: Verify Flow Balance Using Conductivity. An important step to estimating freshwater loading is to construct a conductivity balance of the system to ensure that the model is correctly estimating freshwater inflows and tidal exchange. Electrical conductivity measures the salt content (salinity) of water, and the major salts are considered a conservative (non-reactive) tracer. To accomplish this, conductivity data from TCEQ stations and from the NOAA gage were used as a conservative tracer to determine the flow balance of each reach. The conductivity balance calculation for each reach is represented as:

$$C_t V_t = C_{t-1} V_{t-1} + \sum C_{in} V_{in} - \sum C_{out} V_{out} + C_f V_f \qquad (6)$$

Where: V_t = volume of reach at time step t [m^3]

V_{t-1} = volume of reach at time step t-1 [m^3]

V_f = freshwater volume [m^3]

V_{in}, V_{out} = tidally influenced volumes for time step t [m^3]

C_t = conductivity in the reach [µS/cm]

C_f = conductivity in the freshwater inputs [µS/cm]

C_{in}, C_{out} = conductivity of the tidally influenced flows [µS/cm]

The average conductivity values for the existing water quality monitoring stations were used to define the initial conductivity levels in the model reaches. Conductivity data from station 11499 was used to determine downstream boundary conditions. Conductivity in freshwater (runoff, tributaries and effluent) was assumed equal to 500 µS/cm. Tidally influenced volumes were calculated using Equation 1 and freshwater volumes as described earlier. Using the above information Equation 6 was solved for the conductivity in the reach (C_t). The computed conductivity levels were then compared to existing measurements within the impaired waterbody to corroborate that the flows are accurately represented throughout the system. Figure 4-6 presents a comparison of observed and modeled average conductivity concentrations along Tidal Armand and Horsepen Bayous.

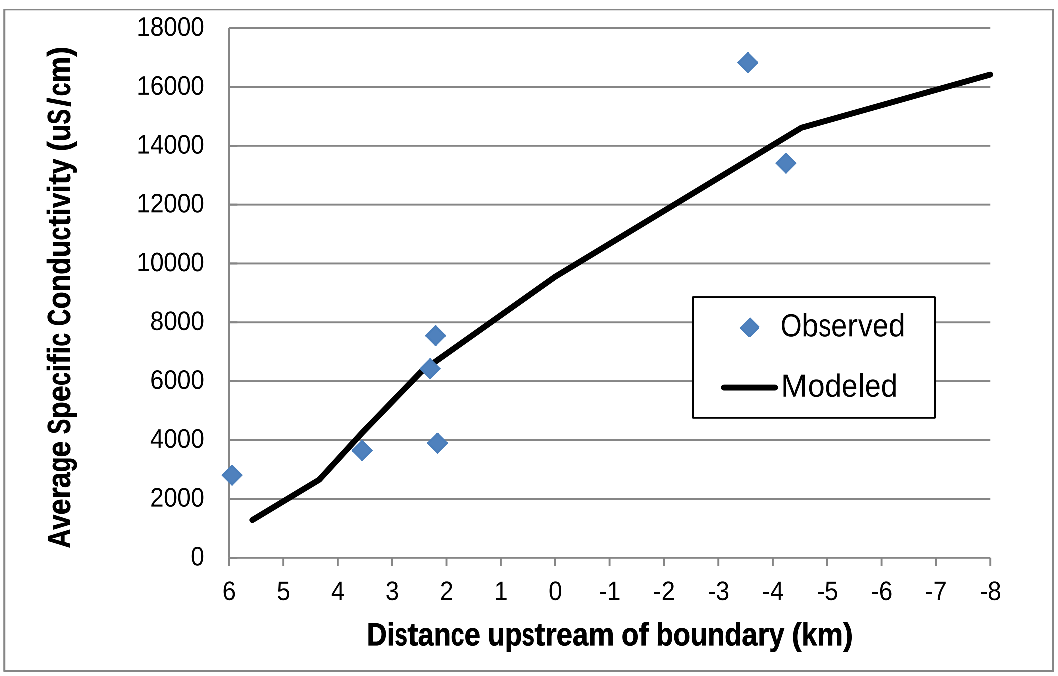

Figure 4-6 Longitudinal Profile of Average Conductivity

Step 6: Perform Mass Balance on Enterococci Levels. Upon validation of the flow balance, a mass-balance on Enterococci for each reach can be computed as follows:

$$N_t V_t = N_{t-1} V_{t-1} + \sum N_{in} V_{in} - \sum N_{out} V_{out} + N_f V_f - k N_{t-1} V_{t-1} \quad (7)$$

Where: N_t = Enterococci level in the reach [counts/dL]

N_f = Enterococci level in the freshwater flow [counts/dL]

N_{in}, N_{out} = Enterococci level in tidally influenced flow [counts/dL]

k = Enterococci first-order decay rate [hr^{-1}]

The average Enterococci concentrations measured at each of the water quality monitoring stations along Armand BayouTidal, Horsepen Bayou and tributaries were used to define the initial conditions in each model reach. The geometric mean of Enterococci concentrations measured in Armand Bayou station 115455 (18 counts/dL) was used to set the downstream boundary concentration of Enterococci. Enterococci levels in runoff, tributaries and WWTFs were estimated as described in Steps 2 and 3.

The model was calibrated by varying the decay rate by reach and adjusting this decay rate within the bounds of reported rates until the model accurately reproduced the temporal and spatial distribution of observed Enterococci within the system. Sinton, *et al*. (1994) and Davies-Colley, *et al*. (1998) reported decay rates between 0.12 and 40 day^{-1}, Anderson, *et al*. (2005) reported rates between 0.73 and 2.1 day^{-1}, and Kay, *et al*. (2005) measured decay rates between 2.2 and 8.5 day^{-1}. Final decay rates applied to the model ranged from 0.5 to 1.2 day^{-1}, which is within the ranges reported in the literature. The decay rates were not varied temporally because insufficient data were available to estimate the seasonal variation in decay rates. The calibrated spreadsheet model is included in Appendix J in electronic format.

Figure 4-7 presents a comparison of measured and modeled Enterococci concentrations along the main stem of Armand and Horsepen Bayou. As can be seen, the model reasonably predicts the spatial distribution of Enterococci along the creek. For the tidal prism model, indicator bacteria data (including fecal coliform and *E. coli*), from 2010 through 2012 for a given station were used to compare to modeled values. Fecal coliform and *E. coli* data were converted to Enterococci concentrations using calculated ENT/FC and ENT/EC ratios (0.27 and 0.34, respectively) as previously described.

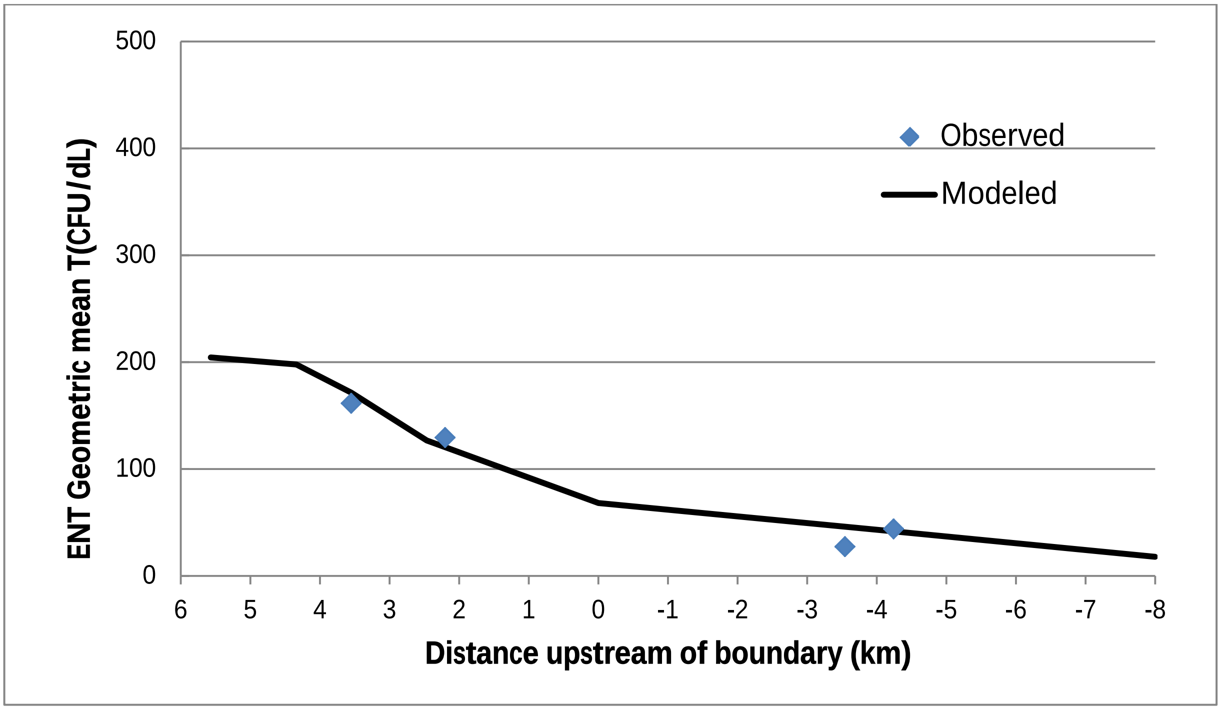

Figure 4-7 Longitudinal Profile of Enterococci Concentrations

Figures 4-8 through 4-10 show time series of Enterococci concentrations for the water quality monitoring stations in the three streams included in this TMDL report. As indicated by the figures, the model reasonably represents the temporal distribution of Enterococci concentrations for the various WQS.

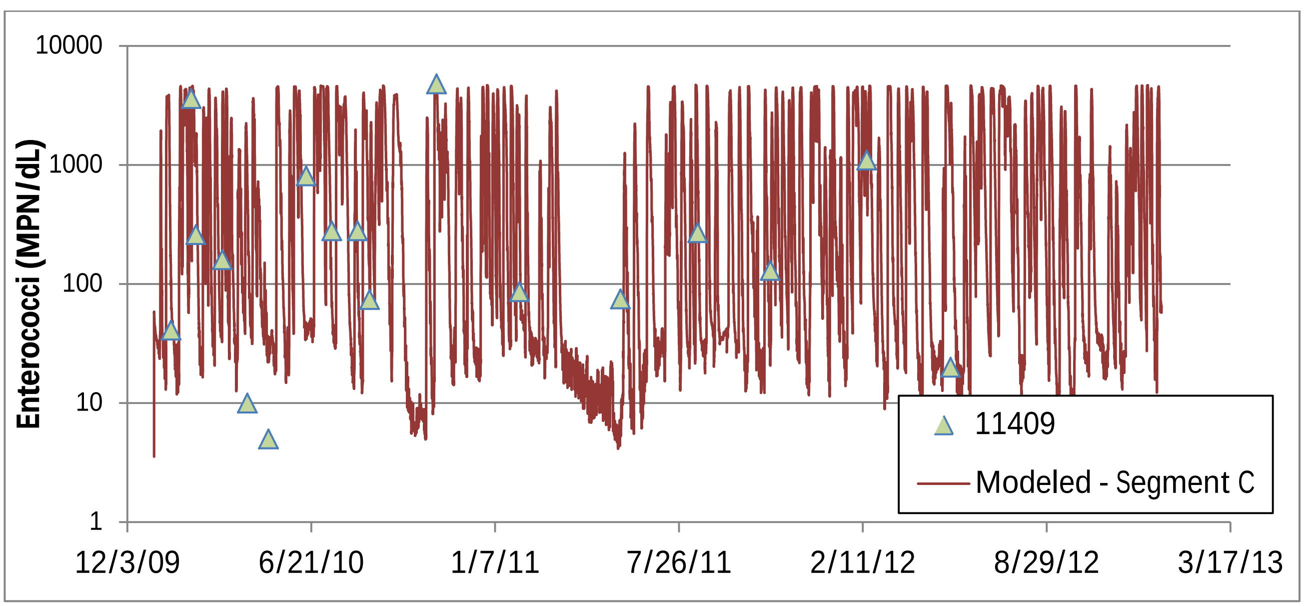

Figure 4-8 Enterococci Levels at Station 11409 (Reach C), Horsepen Bayou (1113B_01)

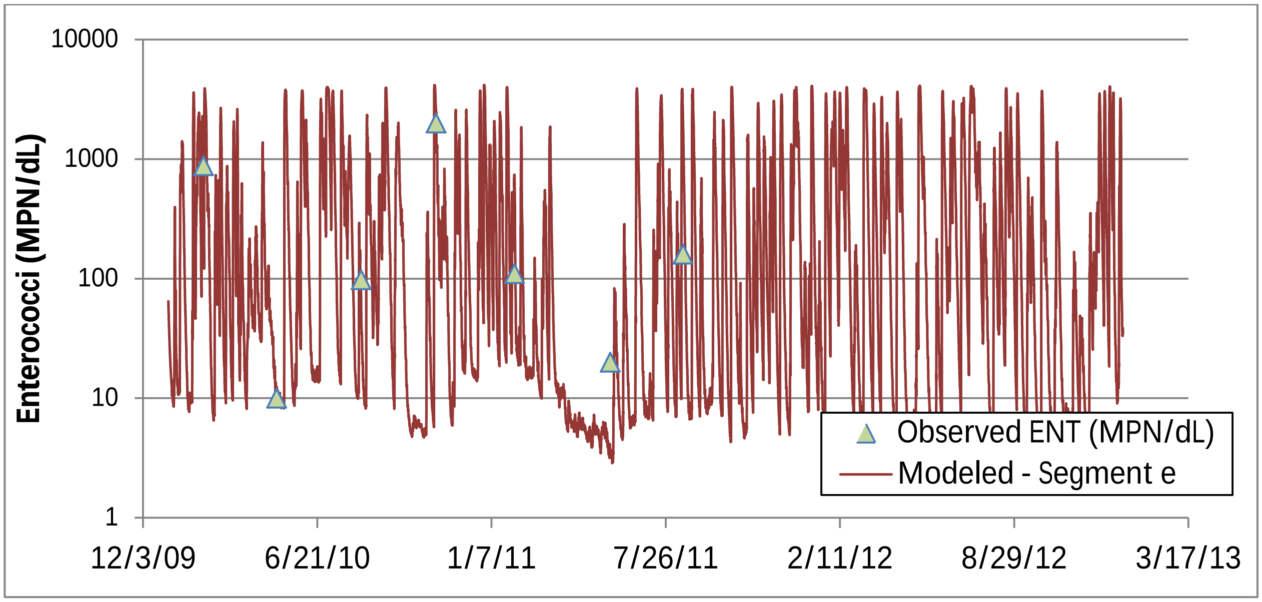

Figure 4-9 Enterococci Levels at Station 17317 (Reach E), Horsepen Bayou (1113B_01)

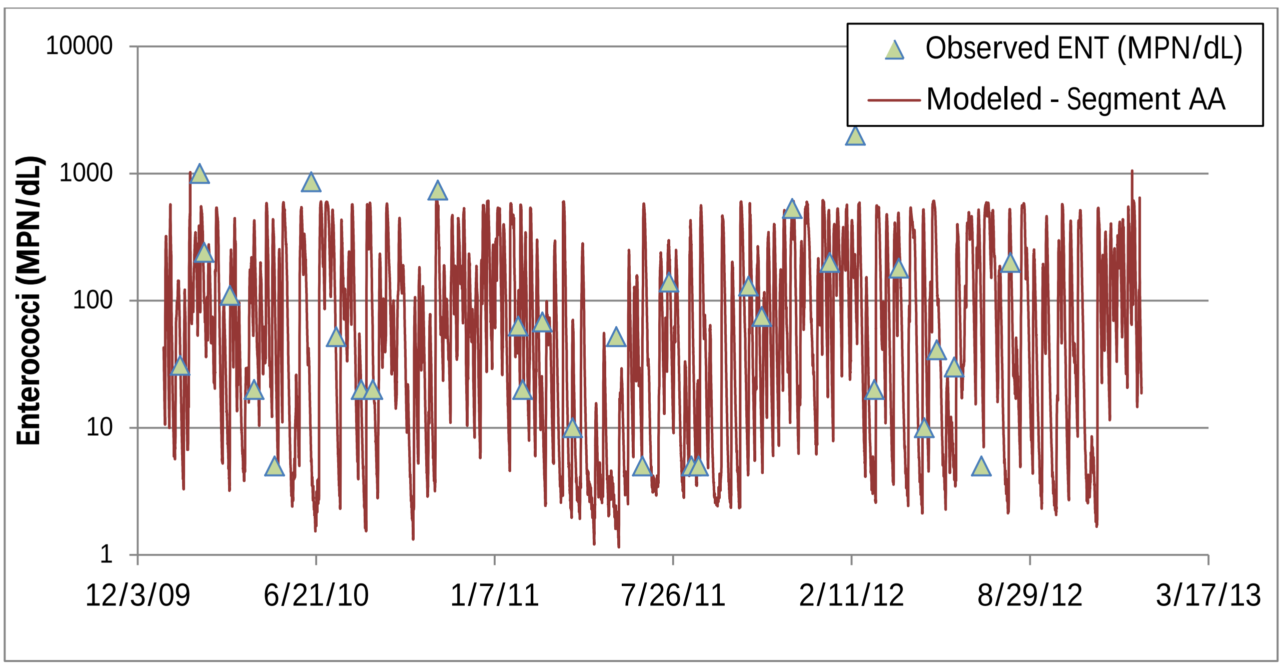

Figure 4-10 Enterococci Levels at Station 11503, Armand Bayou Tidal (1113_02)

4.5.2 Critical Conditions and TMDL Calculation for the Tidal Segments

To calculate the WLA and LA components of the TMDLs for the tidal streams, steps similar to those used for the LDC method are applied. As previously stated, the pollutant load allocation for permitted (point) sources is defined by the WLA. A point source can be either a wastewater (continuous) or stormwater permitted discharge. Stormwater point sources are typically associated with urban and industrialized areas, and recent USEPA guidance includes

NPDES-permitted stormwater discharges as point source discharges and, therefore, part of the WLA.

WLAs may be set to zero for watersheds with no existing or planned continuous permitted point sources. For watersheds with permitted point sources, WLAs may be derived from TPDES permit limits. A WLA may be calculated for each active TPDES wastewater discharger using a mass balance approach as shown in the equation below. The permitted flow rate used for each point source discharge and the water quality criterion concentration are used to estimate the WLA for each wastewater facility. Through TPDES permits WLAs for WWTPs are constant across all flow conditions and ensure that WQS will be attained (USEPA 2007). All WLA values for each TPDES wastewater discharger are then summed to represent the total WLA for the watershed.

*WLA = criterion * permitted flow * unit conversion factor (#/day)*

Where: criterion = 23 CFU/dL (Enterococci)

flow (mgd) = permitted flow

*unit conversion factor = 37,854,120-dL/day*mgd*

Stormwater runoff can contribute both permitted and unregulated sources of bacteria which must also be accounted for in the TMDL allocations. To be consistent with the LDC method, any stormwater runoff originating from the area of a watershed under the jurisdiction of an MS4 permit is considered a point source contribution and is therefore included as part of the WLA calculation. As such the WLA will be split into WWTP WLA and MS4 WLA. Again to be consistent with the LDC method, the estimated loading from stormwater runoff within each drainage area is separated into stormwater loading from MS4 areas and stormwater loading from unregulated areas. This is done by using the percentage of each drainage area covered by the MS4 permit. An explicit MOS of 5 percent of the criterion is also included in the TMDL calculation. The stormwater loading from unregulated areas is considered the LA. Therefore, another way of expressing the LA from unregulated stormwater runoff is calculated as the TMDL minus the margin of safety minus the WLA (sum of WWTP and MS4).

Percent reduction goals were calculated by changing the loads in the tidal prism model until all the reaches have concentrations lower than or equal to the 35 counts/dL criterion for Enterococci. It is noted that the loads coming from upstream freshwater segments, addressed with LDCs, were assumed to be in compliance with the 126 counts/dL criterion for *E. coli* or 42 counts/dL for Enterococci if the 0.34 ratio is used.

The fact that most the WQM stations on the Study Area exceed the geometric mean standard for Enterococci indicates that evaluating mean source inputs (*i.e.*, under mean conditions) via a mass balance approach will be sufficient to ascribe load allocations. The daily load estimates for the simulation period were reduced by a constant such that the geometric mean standard was met (*i.e.*, 33/dL). The percent reduction was computed as follows:

$$\%R = \left(1 - \frac{1}{C_R}\right) \cdot 100 \qquad (8)$$

where C_R is the constant by which the daily Enterococci loadings are reduced and %R is the associated percent reduction in the Enterococci levels.

CHAPTER 5
TMDL CALCULATIONS

5.1 Results of TMDL Calculations

The calculations and results of the TMDLs for the 303(d) listed water bodies in the Study Area are provided in Section 5. The bacteria load allocations derived from the two different technical approaches used for freshwater and tidal water bodies are discussed together in each subsection of Section 5 below.

5.2 Estimated Loading and Critical Conditions

USEPA regulations at 40 CFR 130.7(c) (1) require TMDLs to take into account critical conditions for stream flow, loading, and all applicable water quality standards. To accomplish this, available instream WQM data were evaluated with respect to stream flows, tidal flux, and the magnitude of water quality criteria exceedance. TMDLs are derived for specific indicator bacteria in 303(d) listed water bodies at specific WQM stations based on LDCs for Unnamed Tributary of Mary’s Creek (1102G_01) and a mass balance calculation using a tidal prism for tidal streams.

As previously described in Chapter 4, a LDC was used to calculate the bacteria load at the criterion for the freshwater segment over a range of flow conditions. This calculation produces the maximum bacteria load in the stream without exceeding the instantaneous standard over the range of flow conditions.

The pollutant load allocations and percent reduction goals for each flow regime are summarized in Section 5.8. The highest percent reduction goals for the segment was found to occur in the flow regime with the highest flows (0–20th percentile) and consequently, this was the flow regime used to estimate the TMDL.

Figure 5-1 represents the LDC for Armand Bayou Above Tidal (1113A_01) is based on *E coli* bacteria measurements at sampling location 11404 (Armand Bayou at Genoa-Red Bluff Rd). The LDC indicates that geometric mean observed *E coli* loading exceeds the TMDL, established using the geometric mean water quality target, under the highest flow regime. A 70% reduction of the observed loads is required in order to meet the TMDL under the high flow condition.

Figure 5-2 represents the LDC for Unnamed Tributary to Horsepen Bayou (1113C_01) is based on *E coli* bacteria measurements at sampling location 17485 (Unnamed Tributary of Horsepen Bayou Tidal at Penn Hills). The LDC indicates that *E coli* levels exceed the geometric mean water quality target under highest and mid-range flow conditions. A 77% reduction of the observed loads is required at the high flow condition and a 36% reduce mid-range flow condition in order to meet the TMDL for both flow conditions.

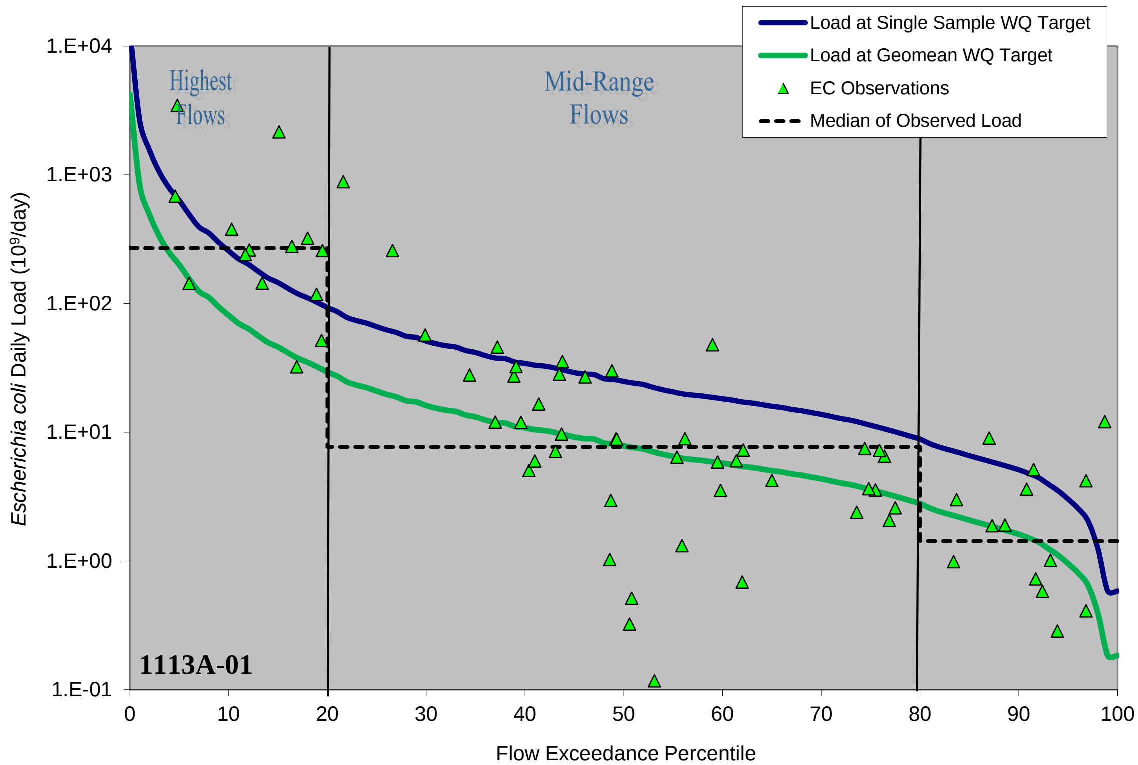

Figure 5-1: Load Duration Curve for Armand Bayou Above Tidal (1113A_01)

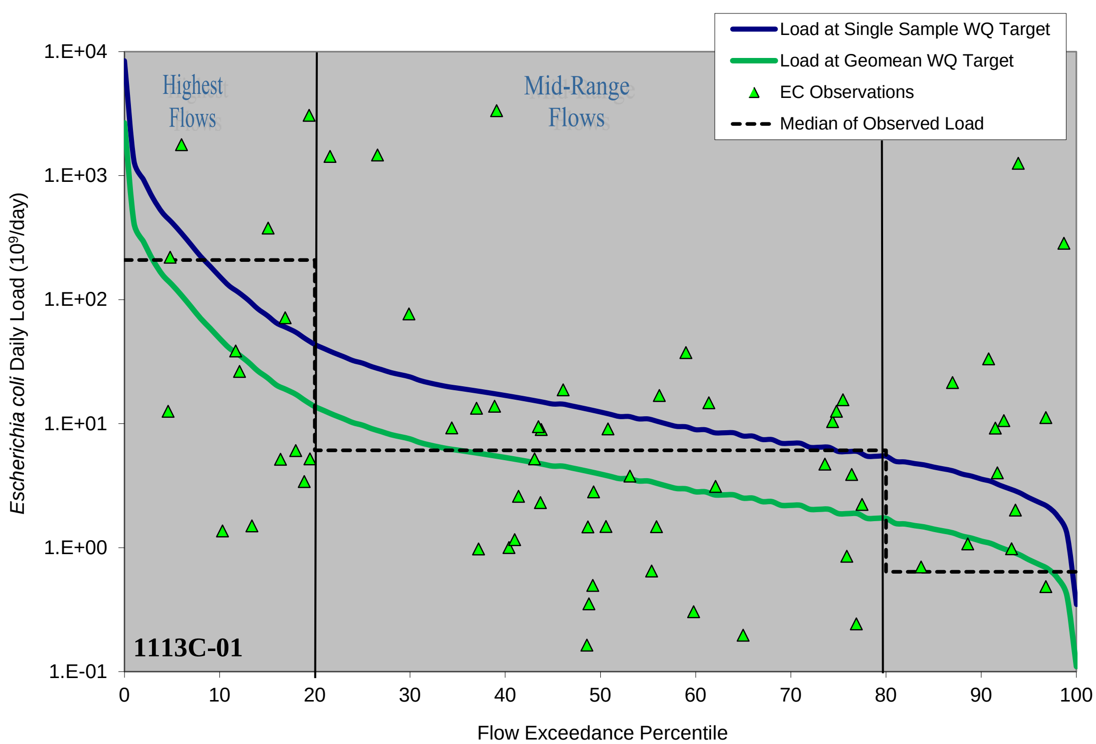

Figure 5-2: Load Duration Curve for Unnamed Tributary to Horsepen Bayou (1113C_01)

Figure 5-3 represents the LDC for Willow Springs Bayou (1113D_01) is based on *E coli* bacteria measurements at sampling location 17487 (Willow Spring at Bandridge Rd in southeast Houston). The LDC indicates that *E coli* levels exceed the instantaneous and geometric mean water quality criteria under all three flow conditions. Load reductions ranging from 70 to 87.5% are required to meet the TMDL across the flow conditions.

Figure 5-4 represents the LDC for Big Island Slough (1113E_01) is based on *E coli* bacteria measurements at sampling location 17486 (Big Island Slough at Hillridge Rd). The LDC indicates that *E coli* levels exceed the instantaneous and geometric mean water quality criteria under all three flow conditions. Load reductions ranging from 72.5 to 89.6% are required to meet the TMDL across the flow conditions.

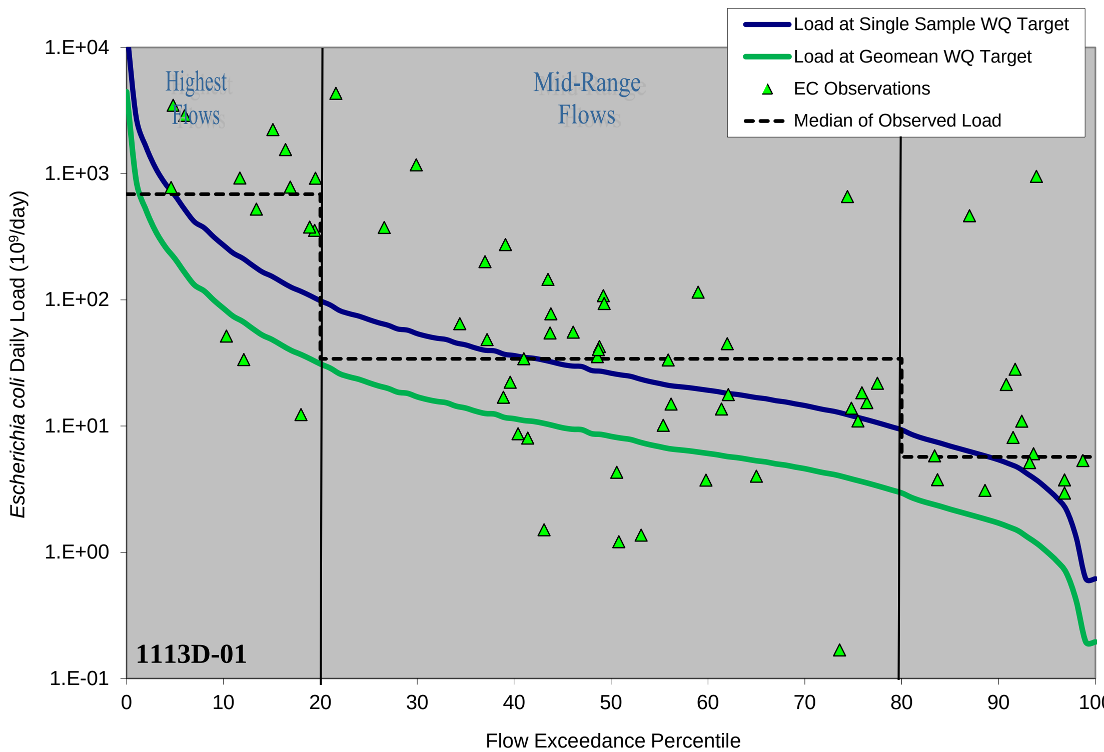

Figure 5-3: Load Duration Curve for Willow Springs Bayou (1113D_01)

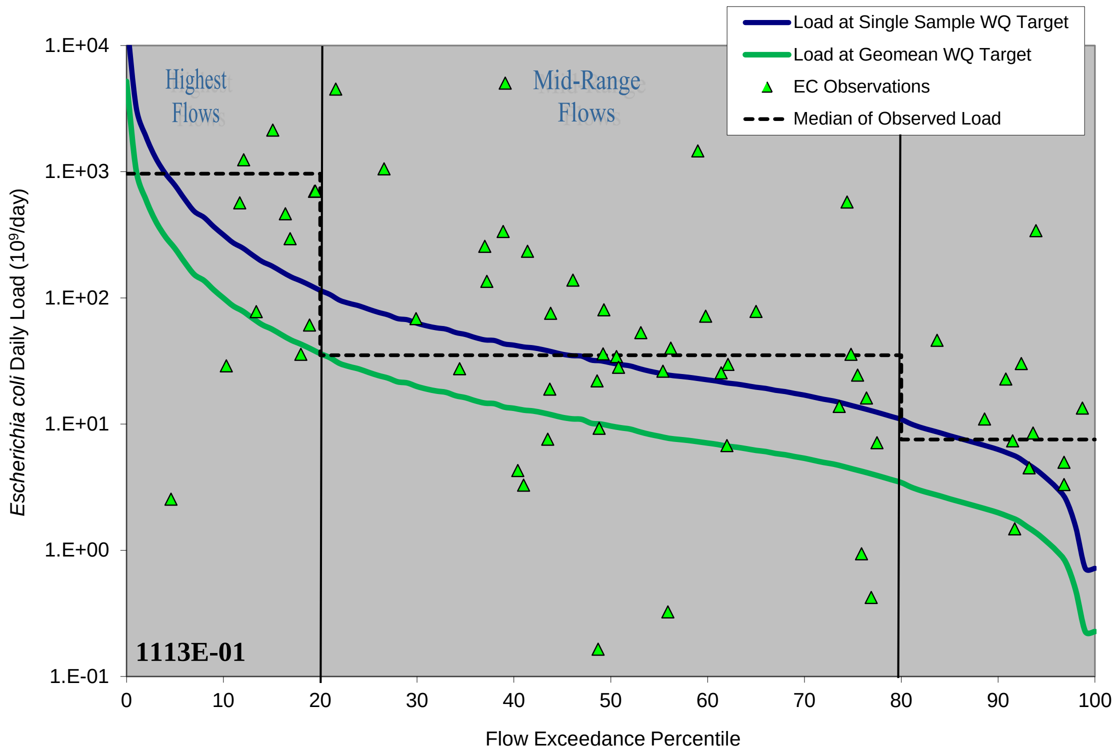

Figure 5-4: Load Duration Curve for Big Island Slough (1113E_01)

Existing Enterococci loads to the TMDL tidal segments are summarized in Table 5-1. The estimated existing loads are calculated as the sum of runoff, tributary, and WWTF loads to model reaches C (Horsepen Bayou), E (Horsepen Bayou), and Armand Bayou Tidal (1113_02).

Table 5-1 Estimated Existing Enterococci Loads to TMDL Tidal Segments

Segment	Receiving Stream	Enterococci Load (counts/day)
1113B_01	Horsepen Bayou (Reach C)	2.39E+07
1113B_01	Horsepen Bayou (Reach E)	2.45E+08
1113_02	Armand Bayou Tidal	2.32E+08

The percent reduction goals that are required to meet the geometric mean standard for contact recreation in the TMDL tidal segments are illustrated in Figure 5-2. The required load reductions were calculated at the end of the reach containing the sampling location. Required load reductions are summarized in Table 5-2.

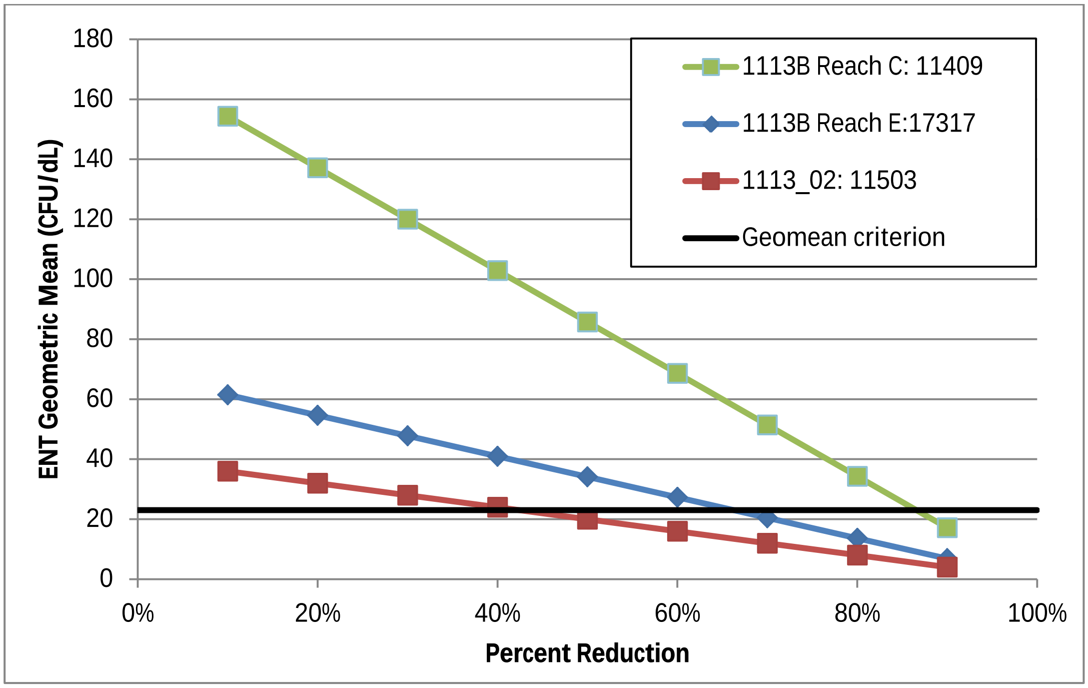

Figure 5-2 Contact Recreation Standards Attainment for Tidal Segments

Table 5-2 TMDL Percent Reductions Required to Meet Contact Recreation Standard for Tidal Segments

Segment	Sampling Location	Stream Name	Percent Reduction Required
1113B_01	11409	Horsepen Bayou (Reach C)	86.59%
1113B_01	17317	Horsepen Bayou (Reach E)	66.31%
1113_02	11503	Armand Bayou Tidal	42.48%

5.3 Wasteload Allocation

TPDES-permitted facilities are allocated a daily wasteload calculated as their permitted discharge flow rate multiplied by one half of the instream geometric mean water quality criterion. Table 5-1 summarizes the WLA for the TPDES-permitted facilities within the Study Area. The WWTFs will not be subject to all listed indicator bacteria. The WLA for each facility (WLA_{WWTF}) is derived from the following equation:

*WLA_{WWTF} = criterion * flow * unit conversion factor (#/day)*

Where:

criterion = 23 and 126/2 counts/dL for enterococci and E coli, respectively *flow (10^6 gal/day) = permitted flow*

unit conversion factor = 37,854,120-10^6gal/day

When multiple TPDES facilities occur within a watershed, loads from individual WWTFs are summed and the total load for continuous point sources is included as part of the WLA_{WWTF} component of the TMDL calculation for the corresponding segment. When there are no TPDES WWTFs discharging into the contributing watershed of a WQM station, then WWTF WLA is zero. Compliance with the WLA_{WWTF} will be achieved by adhering to the fecal coliform discharge limits and disinfection requirements of TPDES permits.

Stormwater discharges from MS4 areas are considered permitted point sources. Therefore, the WLA calculations must also include an allocation for permitted stormwater discharges. Given the limited amount of data available and the complexities associated with simulating rainfall runoff and the variability of stormwater loading a simplified approach for estimating the WLA_{MS4} areas was used in the development of these TMDLs. For both the LDC and tidal prism method the percentage of each watershed that is under a TPDES MS4 permit is used to estimate the amount of the overall runoff load that should be dedicated as the permitted stormwater contribution in the $WLA_{STORMWATER}$ component of the TMDL. The difference between the total stormwater runoff load and the portion allocated to $WLA_{STORMWATER}$ constitutes the LA component of the TMDL (direct nonpoint runoff).

Table 5-3: Wasteload Allocations for TPDES-Permitted Facilities

TPDES Number	NPDES NUMBER	Facility Name	Final Permitted Flow (MGD)	Enterococci (counts/day)
10495-152	TX0069736	Metro Central WWTP	5	4.35E+09
10539-001	TX0022543	Robert Savely Water Reclamation Facility	10	8.71E+09
03523-000	TXL005000	City of Houston Sludge Plant	n/a	n/a
03029-000	TX0103900	Equistar Chemicals Bayport Complex	n/a	n/a

For the freshwater stream, the flow dependent calculations for the MS4 portion of the WLA are derived using LDC and the MS4 percentages provided in Table 3-5

5.4 Load Allocation

As discussed in Section 3, unregulated sources of bacteria loading to the receiving streams of each waterbody emanate from a number of different sources. The data analyses demonstrate that exceedances at the WQM stations are the result of a variety of nonpoint source loading. The LAs for each stream segment are calculated as the difference between the TMDL, MOS, WLA, and WLA for MS4 as follows:

$LA = TMDL - \sum WLA_{WWTF} - \sum WLA_{STORMWATER} - MOS$

Where:

LA = allowable load from unregulated sources
TMDL= total allowable load
ΣWLA_{WWTF} = sum of all WWTF loads
$\sum WLA_{STORMWATER}$ = sum of all Stormwater loads
MOS = margin of safety

5.5 Seasonal Variability

Federal regulations (40 CFR §130.7(c)(1)) require that TMDLs account for seasonal variation in watershed conditions and pollutant loading. Seasonal variation was accounted for in these TMDLs by using more than 5 years of water quality data and by using the longest period of USGS flow records when estimating flows to develop flow exceedance percentiles.

Analysis of the available data for *E coli* and enterococci in Table 1-13 showed no consistent trend among all evaluated stations for water and/or cooler months.

5.6 Allowance for Future Growth

Compliance with these TMDLs is based on keeping the indicator bacteria concentrations in the selected waters below the limits that were set as criteria for the individual sites. Future growth of existing or new point sources is not limited by these TMDLs as long as the sources do not cause indicator bacteria to exceed the limits. The assimilative capacity of streams increases as the amount of flow increases. Increases in flow allow for additional indicator bacteria loads if the concentrations are at or below the contact recreation criterion. The addition of any future wastewater discharge facilities will be evaluated on a case-by-case basis.

To account for the high probability that new additional flows from WWTF may occur in any of the segments, a provision for future growth was included in the TMDL calculations by estimating permitted flows to year 2050 using population projections completed by the Texas Water Development Board. A summary of the methodology used to predict waste water flow capacity based on population growth is included in Appendix K. For the freshwater segments, only Big Island Slough (1113E_01) does not already have area completely serviced by WWTF(s) outside of the AU watershed. An estimated future flow increase of 0.5 MGD was applied to determine the future growth load in Big Island Slough (1113E_01). For the tidally influenced segments, only Horsepen Bayou (1113B_01) contains WWTFs, while the area in Armand Bayou Tidal (1113_02) is completely serviced by a WWTF outside the AU watershed boundary. Loads were calculated using the projected flows and a 23 counts/dL concentration were input in the tidal prism model along with all the other existing loads. The loads were then reduced by different percentages until the contact recreation criterion was met in all the reaches. The reduced loads were then added to calculate the assimilative capacity or $TMDL_{future}$. In both cases, the WLA_{WWTF} for future population growth is the difference between the $TMDL_{future}$ and the TMDL calculated using current conditions.

5.7 Margin of Safety

Federal regulations (40 CFR §130.7(c)(1)) require that TMDLs include an MOS. The MOS is a conservative measure incorporated into the TMDL equation that accounts for the uncertainty associated with calculating the allowable pollutant loading to ensure geometric mean criterion are attained. USEPA guidance allows for use of implicit or explicit expressions of the MOS, or both. When conservative assumptions are used in development of the TMDL, or conservative factors are used in the calculations, the MOS is implicit. When a specific percentage of the TMDL is set aside to account for uncertainty, then the MOS is considered explicit.

The TMDL for the freshwater segment incorporates an explicit MOS by setting a more stringent target for indicator bacteria loads that is 5 percent lower than the single sample criterion. The explicit margin of safety was used because of the limited amount of data. For contact recreation, this equates to a single sample target of 379 MPN/100mL for *E coli* and a geometric mean target of 120 MPN/100mL. The net effect of the TMDL with MOS is that the assimilative capacity or allowable pollutant loading of each waterbody is slightly reduced. The TMDL for the freshwater stream in this report incorporate an explicit MOS in the LDC by using 95 percent of the single sample criterion. For the tidal segments, the MOS was also explicit. But in this case, the MOS was based on allowable loading, not concentration. After the tidal prism model calculated the total assimilative capacity for enterococci (the TMDL), 5 percent of the allowable load was computed as the MOS.

5.8 TMDL Calculations

The bacteria TMDLs for the 303(d)-listed WQM stations covered in this report were derived using LDCs and the tidal prism model. A TMDL is expressed as the sum of all WLAs (point source loads), LAs (nonpoint source loads), and an appropriate MOS, which attempts to account for uncertainty concerning the relationship between effluent limitations and water quality.

This definition can be expressed by the following equation:

$$TMDL = \Sigma\ WLA + \Sigma\ LA + MOS + Future\ Growth$$

Tables 5-2 through 5-5 summarize the pollutant load allocations and percent reduction goals at current flows, for each flow regime, for the freshwater segments. Tables 5-4 through 5-8 summarize the estimated maximum allowable load of *E coli* for the freshwater assessment units included in this project while tidal stream segments are summarized in Table 5-9. These are calculated from the tidal prism model based on average percent reductions from total existing loading (WWTFs, runoff and tributaries) to the water body (Table 5-2).

Table 5-4: E coli TMDL Calculations for Armand Bayou Above Tidal (1113A_01)

Station 11404			
Flow Regime %	**0%-20%**	**20%-80%**	**80%-100%**
Median Flow, Q (cfs)	27.7	2.7	0.6
Observed Geomean Load (10^9 org/day)	2.70E+02	7.70E+00	1.43E+00
TMDL (Q*C) (10^9 org/day)	8.53E+01	8.25E+00	1.70E+00
MOS (Q*C*0.05) (10^9 org/day)	4.26E+00	4.12E-01	8.49E-02
Allowable Load at Water Quality Target,	8.10E+01	7.83E+00	1.61E+00
Load Reduction (10^9 org/day)	1.89E+02	0.00E+00	0.00E+00
Load Reduction (%)	70.0%	0.0%	0.0%
TMDL (Qfuture*WQS) (10^9 org/day)	0.00E+00		

Table 5-5: E coli TMDL Calculations for Unnamed Tributary to Horsepen Bayou (1113C_01)

Station 17485			
Flow Regime %	**0%-20%**	**20%-80%**	**80%-100%**
Median Flow, Q (cfs)	16.6	1.3	0.4
Observed Geomean Load (10^9 org/day)	2.09E+02	6.10E+00	6.38E-01
TMDL (Q*C) (10^9 org/day)	5.11E+01	4.12E+00	1.19E+00
MOS (Q*C*0.05) (10^9 org/day)	2.56E+00	2.06E-01	5.94E-02
Allowable Load at Water Quality Target,	4.86E+01	3.92E+00	1.13E+00
Load Reduction (10^9 org/day)	1.60E+02	2.18E+00	0.00E+00
Load Reduction (%)	76.7%	35.8%	0.0%
TMDL (Qfuture*WQS) (10^9 org/day)	0.00E+00		

Table 5-6: E coli TMDL Calculations for Willow Springs Bayou (1113D_01)

Station 17487			
Flow Regime %	**0%-20%**	**20%-80%**	**80%-100%**
Median Flow, Q (cfs)	29.2	2.8	0.6
Observed Geomean Load (10^9 org/day)	6.87E+02	3.41E+01	5.70E+00
TMDL (Q*C) (10^9 org/day)	9.01E+01	8.71E+00	1.79E+00
MOS (Q*C*0.05) (10^9 org/day)	4.50E+00	4.35E-01	8.96E-02
Allowable Load at Water Quality Target,	8.56E+01	8.27E+00	1.70E+00
Load Reduction (10^9 org/day)	6.01E+02	2.58E+01	4.00E+00
Load Reduction (%)	87.5%	75.7%	70.1%
TMDL (Qfuture*WQS) (10^9 org/day)	0.00E+00		

Table 5-7: E coli TMDL Calculations for Big Island Slough (1113E_01)

Station 17486			
Flow Regime %	**0%-20%**	**20%-80%**	**80%-100%**
Median Flow, Q (cfs)	34.1	3.3	0.7
Observed Geomean Load (10^9 org/day)	9.63E+02	3.51E+01	7.53E+00
TMDL (Q*C) (10^9 org/day)	1.05E+02	1.02E+01	2.09E+00
MOS (Q*C*0.05) (10^9 org/day)	5.25E+00	5.08E-01	1.05E-01
Allowable Load at Water Quality Target,	9.98E+01	9.65E+00	1.99E+00
Load Reduction (10^9 org/day)	8.63E+02	2.55E+01	5.55E+00
Load Reduction (%)	89.6%	72.5%	73.6%
TMDL (Qfuture*WQS) (10^9 org/day)	4.35E+-01		

Table 5-8: E coli TMDL Summary Calculations for Non-tidal Segments

Assess-ment Unit	Stream Name	Indicator Bacteria	TMDL[a] (MPN/day)	WLA_{WWTF}[b] (MPN/day)	$WLA_{STORMWATER}$[c] (MPN/day)	LA[d] (MPN/day)	MOS[e] (MPN/day)	Future Growth[f] (MPN/day)
1113A_01	Armand Bayou Above Tidal	*E coli*	8.53E+10	0.00E+00	8.10E+10	0.00E+00	4.26E+09	0.00E+00
1113C_01	Unnamed Tributary to Horsepen Bayou	*E coli*	5.11E+10	0.00E+00	4.86E+10	0.00E+00	2.56E+09	0.00E+00
1113D_01	Willow Springs Bayou	*E coli*	9.01E+10	0.00E+00	8.56E+10	0.00E+00	4.50E+09	0.00E+00
1113E_01	Big Island Slough	*E coli*	1.05E+11	0.00E+00	9.32E+10	6.57E+09	5.25E+09	1.19E+09

[a] *Maximum allowable load for the flow range requiring the highest percent reduction (Table 5-4)*
[b] *Sum of loads from the WWTF discharging upstream of the TMDL station. Individual loads are calculated as permitted flow * 126/2 (E coli) MPN/100mL*conversion factor (Table 5-3)*
[c] *$WLA_{STORMWATER}$ = (TMDL – MOS –WLA_{WWTF})*(percent of drainage area covered by stormwater permits)*
[d] *LA = TMDL – MOS –WLA_{WWTF} –$WLA_{STORMWATER}$-Future growth*
[e] *MOS = TMDL x 0.05*
[f] *Projected increase in WWTF permitted flows*126/2*conversion factor*

Table 5-9: TMDL Calculations for Tidal Segments

Assess-ment Unit	Stream Name	Indicator Bacteria	TMDL[a] (MPN/day)	WLA_{WWTF}[b] (MPN/day)	$WLA_{STORMWATER}$[c] (MPN/day)	LA[d] (MPN/day)	MOS[e] (MPN/day)	Future Growth[f] (MPN/day)
1113_02	Armand Bayou Tidal	Enterococci	1.26E+12	0.00E+00	1.19E+12	0.00E+00	6.28E+10	0.00E+00
1113B_01	Horsepen Bayou	Enterococci	7.79E+11	1.31E+10	7.27E+11	0.00E+00	3.89E+10	4.23E+09

[a] *Maximum allowable load for the flow range requiring the highest percent reduction (Table 5-4)*
[b] *Sum of loads from the WWTF discharging upstream of the TMDL station. Individual loads are calculated as permitted flow * 126/2 (E coli) MPN/100mL*conversion factor (Table 5-3)*
[c] *$WLA_{STORMWATER}$ = (TMDL – MOS –WLA_{WWTF})*(percent of drainage area covered by stormwater permits)*
[d] *LA = TMDL – MOS –WLA_{WWTF} –$WLA_{STORMWATER}$-Future growth*
[e] *MOS = TMDL x 0.05*
[f] *Projected increase in WWTF permitted flows*23*conversion factor*

CHAPTER 6
PUBLIC PARTICIPATION

To provide focused stakeholder involvement in the Armand Bayou Bacteria TMDL and the implementation phase, a 24 member steering committee was formed. In accordance with House Bill 2912, the group has balanced representation within the watershed and commitment was formalized. TCEQ approved the formation of a Armand Bayou stakeholder group and approved the membership. The group has ground rules and H-GAC maintains a membership roster and has a web page dedicated to the Armand Bayou Bacteria TMDL project: (http://www.h-gac.com/community/water/tmdl/armand-bayou/default.aspx)

The responsibility of each stakeholder on the committee is to communicate project information to others being represented and provide personal/organization perspective on all issues; knowledge of the watershed; comments and suggestions during the project; and solicit input from others. Regular meetings have been held and TCEQ solicits stakeholder comment at each project milestone; and assist stakeholders with communications. H-GAC has assisted TCEQ with the public participation and with a facilitator (M.J. Naquin). As contractors to TCEQ, the University of Houston and Parsons provide technical support and presentations at stakeholder meetings.

CHAPTER 7
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APPENDIX A
AMBIENT WATER QUALITY BACTERIA DATA – 2003 TO 2010

APPENDIX B
USGS FLOW DATA AND ARMAND BAYOU INSTANTANEOUS FLOW DATA*

**** See attached CD***

APPENDIX C
TIDE DATA*

**** See attached CD***

APPENDIX D
DISCHARGE MONITORING REPORTS – 2003 - 2013

APPENDIX E
WILDLIFESPECIES LIST

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APPENDIX F
GENERAL METHODS FOR ESTIMATING FLOW AT TMDL WQM STATIONS

APPENDIX F
GENERAL METHODS FOR ESTIMATING FLOW AT WQM STATIONS

Because there are no USGS or HCFCD flow gages located in the Armand Bayou Watershed, a procedure was developed for estimating historical flows at multiple locations in Armand Bayou. There are no gage records available for the Bayou other than a handful of individual flow measurement. To support LDC development, ten years of daily flow estimates are needed at the four impaired locations in the Bayou.

7.1 Approach

A statistical model based on historical flows from adjacent Bayous will be used to estimate flows. The flow records for several adjacent Bayous appear to be reliable, complete and are highly correlated among one another. These flow time series will be used to derive candidate flow prediction models. Both linear and nonlinear models were tested but ultimately the nonlinear model was selected as the preferred option for developing flow estimates for the Bayou.

7.2 Data

Extended periods of daily flow records are available on Sims Bayou and Vince Bayou. Sims and Vince are adjacent to Armand Bayou and similar in size and land use. A comparison of the two gages is provided in Table 1. In addition, a summary of land cover for each of the gage drainage areas is presented in Table 2 and compared with the land cover for Armand Bayou. In addition, a graphical comparison of land cover and gage locations is shown in Figure 1.

Table F-7: USGS Gages in the area with a Continuous Period of Record from 2002-2012

Gage Number	Name	Percent		Drainage Area (acres)	Mean Flow (cfs)	Number of Continuous Data Points
		Developed Land	Forest/Wetland			
08075730	Vince Bayou at Pasadena, TX	98%	1%	4,863	17.3	4018
08075400	Sims Bayou at Hiram Clarke St, Houston, TX	78%	7%	13,279	38.8	4018

Table F-2: Land Cover Summary

	1113A_01		1113C_01		1113D_01		1113E_01		Sims		Vince	
Land cover class	Acres	%	Acres	%	Acres	%	Acres	%	Acres	%	Acres	%
Open Water	41	1%	0	0%	38	1%	61	1%	116	1%	12	0%
Developed, Open Space	631	17%	215	12%	1089	22%	869	17%	2424	18%	679	14%

	1113A_01		1113C_01		1113D_01		1113E_01		Sims		Vince	
Land cover class	Acres	%	Acres	%	Acres	%	Acres	%	Acres	%	Acres	%
Developed, Low Intensity	809	22%	327	18%	783	16%	745	15%	2791	21%	1125	23%
Developed, Medium Intensity	1178	32%	1032	58%	1607	33%	1293	25%	4403	33%	2043	42%
Developed, High Intensity	511	14%	190	11%	392	8%	483	9%	698	5%	927	19%
Barren Land	10	0%	0	0%	25	1%	32	1%	40	0%	2	0%
Deciduous Forest	50	1%	7	0%	32	1%	81	2%	639	5%	41	1%
Evergreen Forest	1	0%	0	0%	15	0%	20	0%	58	0%	0	0%
Mixed Forest	3	0%	0	0%	2	0%	44	1%	42	0%	0	0%
Shrub/Scrub	39	1%	0	0%	55	1%	47	1%	263	2%	7	0%
Herbaceous	96	3%	5	0%	286	6%	313	6%	332	2%	8	0%
Hay/Pasture	162	4%	0	0%	511	10%	271	5%	1250	9%	16	0%
Cultivated Crops	5	0%	0	0%	1	0%	1	0%	1	0%	0	0%
Woody Wetlands	152	4%	0	0%	34	1%	842	16%	222	2%	0	0%
Emergent Herbaceous Wetlands	0	0%	0	0%	0	0%	3	0%	0	0%	0	0%
Total	**3688**	**100 %**	**1777**	**100 %**	**4871**	**100 %**	**5106**	**100 %**	**13279**	**100 %**	**4863**	**100%**
Total Developed	**3129**	**85%**	**1764**	**99%**	**3872**	**79%**	**3389**	**66%**	**10316**	**78%**	**4775**	**98%**
Total Forest/Wetlan d	**207**	**6%**	**7**	**0%**	**83**	**2%**	**992**	**19%**	**962**	**7%**	**42**	**1%**

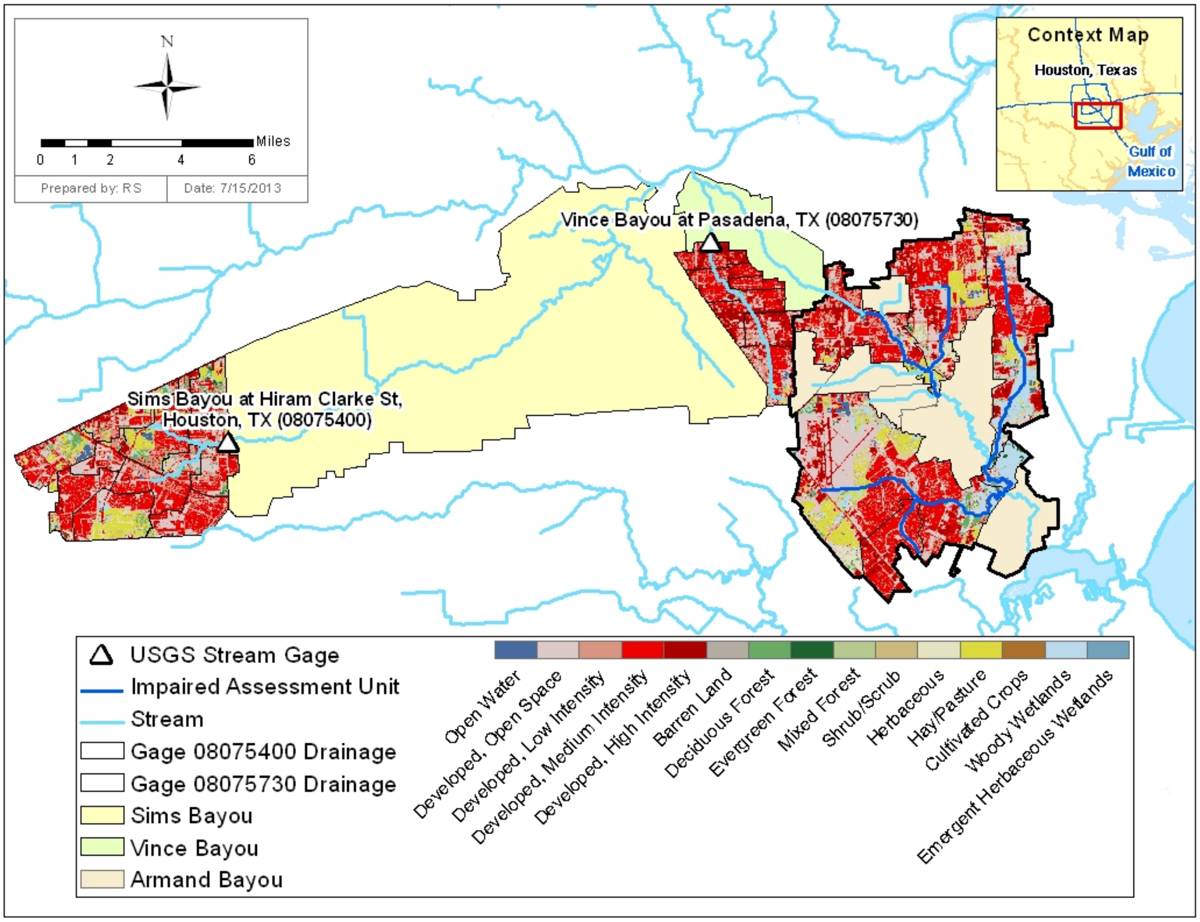

Figure F-7: USGS Gage locations

7.3 Model Development

7.4 <u>Model form</u>

A model is desired that will reliably predict an unknown flow in one location as a function of known flows from other locations with similar weather and land use. Such models can be linear, nonlinear or autoregressive (Linsley, Kohler and Paulhus 1982). In general, they take take the form:

$$Q_{u,t} = f(Q_{k,t}\ Q_{k,t-1}\ldots)$$

Where:

$Q_{u,t}$= unknown flow time series
$Q_{k,t}$= known flow time series;
f(x) = linear or exponential function)

In general the time interval of the data is not important so long as the measurements are contemporaneous and equivalently averaged as there is no such thing as a truly instantaneous flow rate. In this case the input and output of the model are average daily flows. An initial investigation of gage correlation revealed a significant correlation (0.757) between the contemporaneous daily values of Sims and Vince Bayous and much lower values for flows lagged by one day. An analysis in log space produced significant but lower correlations thus a contemporaneous liner model was selected. Next, the model coefficients were selected based on the following model form.

$$Q_u = Q_k A^x D^y W^z$$

Where:

Q_u= unknown flow
Q_k= known flow;

A= Drainage area ratio

D= Developed area ratio

W= Wetland/Forest area ratio

x, y, z = parameters

Note there is no constant term because it is assumed that the unknown flow is zero anytime the known flow is zero. This isn't the case because of treatment plant discharges in Sims Bayou but as discussed below, the gage data were adjusted to remove their effect.

7.5 Parameter Selection

The model parameters were selected using the following process:

- Reasonable model parameters were selected.
- The Sims Bayou gage was used as input to the model, and used to compare to the known flows at Vince Bayou.
- Similarly, the Vince Bayou gage was used as input to the model, and used to compare to the known flows at Sims Bayou
- Through an iterative process, the model parameters were refined to improve the fit for both Sims and Vince Bayou Gages.

A total of three wastewater treatment plants are located in Sims Bayou watershed. In order to properly use the USGS gage flows for the gage correlation approach, it was necessary to establish base flows without the plants. This was accomplished as follows:

- The monthly WWTP flows were obtained for each of the plants
- These flows were totaled to come up with a single WWTP flow for each month
- These flows were subtracted from the Sims Bayou USGS gage flow as shown in equation below.

$$Q_{baseflow} = Q_{USGSgage} - \sum_{\#wwtf}^{1} Q_{Avg.MonthlyWWTF}$$

- When $Q_{baseflow}$ resulted in a negative value, 30% of the USGS flow was used as a representative baseflow. This assumption is based on goodness of fit, best professional judgement and previous studies that showed baseflow is typically 20-40% of typical Houston bayou flows.

7.6 Final Model

The final model parameters used to estimate flows in Armand Bayou watershed were as follows:

- X = 0.224
- Y = 0.274
- Z = 0.072

7.7 Goodness of Fit

A combination of visual evaluation, minimization of daily mean residuals and root mean square error were used to arrive at the model parameters that provided the best fit across a range of flow conditions.

To demonstrate the fit that was achieved using the above model, an example of the flow duration curve developed based on the USGS gage flow for Vince Bayou compared with the projected flows is presented in Figure 3. As shown in the Figure, the fit over the entire range of flow conditions is quite good. The model overpredicts a small amount at the very low flow conditions (i.e., less than the 10th percentile). There is also a small amount of overprediction in the high flows, with mid-range flows being slightly underestimated.

The mean residuals achieved for this comparison and root mean square error is presented in Table 3.

Figure F-3: Vince Bayou Gage Correlation Model Comparison

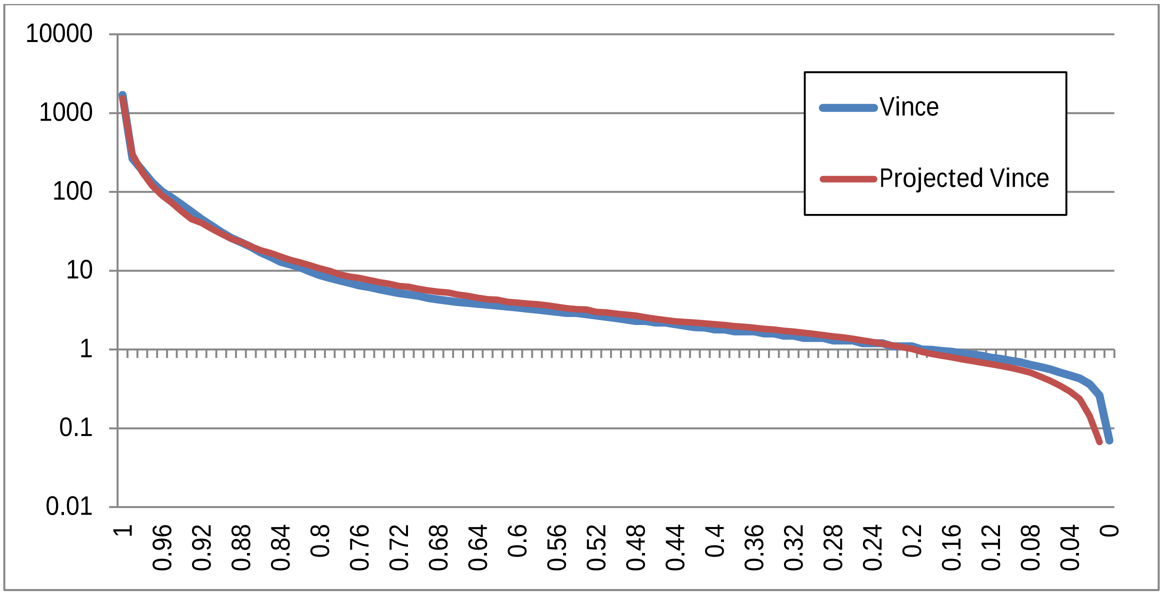

Table F-3: Gage Correlation Model Fit

Gage Number	Name	Mean Daily Residuals (cfs)	Root Mean Square Error (cfs)	No. Data Points
08075730	Vince Bayou at Pasadena, TX	-0.08	46.2	4,018

7.8 Model application

This approach was used to develop flow duration curves for the Study Area. The flow exceedance tables developed using the gage correlation model are presented in Table F-4.

Table F-4: Flow Exceedance Percentiles (cfs)

Percentile	1113_A	1113_C	1113_D	1113_E
10	0.55	0.39	0.58	0.68
20	0.95	0.59	1.01	1.17
30	1.49	0.75	1.57	1.83
40	1.96	0.96	2.07	2.42
50	2.67	1.34	2.82	3.29
60	3.70	1.82	3.90	4.55
70	5.50	2.57	5.81	6.78
80	10.03	4.69	10.59	12.36
90	27.67	16.59	29.21	34.07
100	1439.94	909.62	1520.48	1773.36

APPENDIX G
TIDAL MODEL CROSS-SECTIONS

APPENDIX H
TRIBUTARY INFLOWS AND LOADS

APPENDIX I
RUNOFF INFLOWS AND LOADS

APPENDIX J
TIDAL PRISM MASS BALANCE MODEL

APPENDIX K
METHOD FOR ESTIMATING FUTURE WWTF PERMITTED FLOWS

Appendix K - Methodology to Project Permitted Flows for WWTFs Discharging to the Armand Bayou Watershed

The methodology used to predict future growth to 2050 is based on the approach used in the Clear Creek TMDL report. This appendix describes the procedure used for the growth prediction.

Municipal Wastewater Projections

Municipal wastewater flow projections are based on the population difference between the 2010 census population and the 2050 population estimate from the Texas Water Development Board Region H Population/Demand Estimates (2013). If a WWTF was located within a city, the population growth for that city was used to project future WWTF flows; otherwise, county population projections were used. Table K-1 presents the population estimates for cities and counties in the Armand Bayou watershed. In the case of the two WWTFs in the Armand Bayou watershed, the only city of interest is the City of Houston.

Table K-1 Summary of Population Estimates for Armand Bayou Watershed

City	2010 U. S. Census Population	2020 Population Estimate	2050 Population Estimate	Percent Increase (2000-2050)
DEER PARK	32,010	34,255	38,853	21%
HOUSTON	**2,058,056**	**2,201,986**	**2,724,216**	**32%**
LA PORTE	33,800	34,345	35,785	6%
PASADENA	149,043	154,441	167,450	12%
TAYLOR LAKE VILLAGE	3,544	3,557	3,690	4%
WEBSTER	10,400	15,071	17,776	71%

Next, the per capita permitted flow for each city in the watershed was determined for 2010. To do this, permitted flows were obtained for all WWTFs within the cities. According to the City of Houston "Wastewater Facilities & Maintenance Section" website, the City of Houston treats an average of 277 MGD and is permitted to discharge a total of 564 MGD (2013). This value was used to calculate the per capita flow for the City as shown in Table K-2. Using the calculated per capita flow, the future permitted flow for 2050 was projected and is also included in Table K-3. It should be noted that this estimate is lower than would be expected based on typical wastewater generation estimates per person which is expected since portions of the City are served by non-City of Houston WWTFs. However, this estimate was determined to be acceptable for use in this analysis.

Table K-2 Per Capita Flow by City

City	Wastewater generated Per Capita (gallons per day)	Total permitted flow (MGD) - 2010	Total permitted flow (MGD) - 2050
Houston	2.74E-04	564	746.6

For WWTFs within city limits, the amount of the city's flow made up by the facility was determined. In both cases for the WWTFs in the Armand Bayou watershed, the entire WWTF contributing area was within the boundaries of the City of Houston. Therefore, the calculated future permitted flow for each plant is determined as follows:

- The percentage of City flow is calculated by taking the permitted flow for each plant divided by the current total City permitted flow
- The estimated 2050 Permitted flow is then the percentage of City Flow multiplied by the Total permitted flow for the City of Houston provided in Table K-2.

The results of this analysis are shown in Table K-3.

Table K-3 Summary of Future Permitted Flows by WWTF

TCEQ Permit	Permittee	Location of Outfall	2010 Permitted Flow (MGD)	% of City Flow	Estimated 2050 Permitted Flow (MGD)
10495-152	Metro Central WWTP	City of Houston	5	0.9%	6.62
10539-001	Robert Savely Water Reclamation Facility	City of Houston	10	1.8%	13.24

It should be noted that TCEQ Permit 03523-000 is associated with a City of Houston sludge plant which permitted as a no-discharge facility. Therefore, this facility was not included in future WWTF growth estimates.

Industrial Wastewater Projections

There is one NPDES/TPDES industrial permits within the Armand Bayou watershed, TCEQ permit 03029-000 which is issued to Equistar Chemicals Bayport Complex. This facility is permitted to discharge industrial stormwater and therefore, is not included in this analysis for wastewater projections.

Summary

A summary of the future growth calculations and resulting value is presented in Table K-4.

Table K-4 Flow Projections

Permit #	Facility	Permitted Flow (MGD)	Receiving Segment	Use Pop Projection from	GPCD[a]	Pop 2050[b]	% Flow In City[c]	Flow 2050[d] (MGD)	Adj Flow 2050[e] (MGD)
10495-152	Metro Central WWTP	5	1113B-01	City of Houston	2.74E-04	2,724,216	0.9%	6.62	1.618
10539-001	Robert Savely Water Reclamation Facility	10	1113B-01	City of Houston			1.8%	13.24	3.237

[a] *From Table K-2*
[b] *From Table K-1*
[c] *Permitted flow for facility/total permitted flow for the city in which the facility is located*
[d] *GPCD*Population 2050*%flow in city*
[e] *Flow 2050-Current permitted flow*

Table K-5 Projected Flows by Watershed

Segment	Stream Name	Projected Permitted Flow (MGD)
1113_02	Armand Bayou Tidal	NA
1113A_01	Armand Bayou Above Tidal	NA
1113B_01	Horsepen Bayou	19.86
1113C_01	Unnamed Tributary to Horsepen Bayou	NA
1113D_01	Willow Springs Bayou	NA
1113E_01	Big Island Slough	NA

NA = Allocation not applicable at this time. There are no WWTFs discharging to the Assessment Unit.