TECHNICAL SUPPORT DOCUMENT: INDICATOR BACTERIA TOTAL MAXIMUM DAILY LOADS FOR THE HALLS BAYOU WATERSHED, HOUSTON, TEXAS (1006D_01, 1006D_02, 1006I_01, 1006J_01)

Prepared for:

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

Prepared by:

University of Houston

and

PARSONS

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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
cfu	colony- forming units
CN	curve number
dL	deciliter
DMR	discharge monitoring report
E. coli	Escherichia coli
FDC	flow duration curve
GIS	geographic information system
HCFCD	Harris County Flood Control District
HCOEM	Harris County Office of Homeland Security and Emergency Management
H-GAC	Houston-Galveston Area Council
LA	load allocations
LDC	load duration curve
mL	milliliter
MOS	margin of safety
MPN	most probable number
MS4	municipal separate storm sewer discharge
NED	National Elevation Database
NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
NRCS	National Resources Conservation Service
OSSF	onsite sewage facility
RMSE	root mean square error
SSO	sanitary sewer overflow
STATSGO	State Soil Geographic Database
SWQS	surface water quality standards
TAC	Texas Administrative Code
TCEQ	Texas Commission on Environmental Quality
TMDL	Total Maximum Daily Loads
TPDES	Texas Pollution Discharge Elimination System
TSARP	Tropical Storm Allison Recovery Project
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WLA	wasteload allocation
WQM	water quality monitoring
WWTF	wastewater treatment facility

SECTION 1
INTRODUCTION

Twenty-seven segments in the general Houston Metropolitan Area are considered impaired water bodies for contact recreation because they do not meet indicator bacteria (*Escherichia coli* [*E. coli*]) water quality standards. These segments are in a number of watersheds in the San Jacinto River basin, including Greens Bayou Watershed, Halls Bayou Watershed, Hunting Bayou Watershed, Brays Bayou Watershed, Sims Bayou Watershed, and the general Houston Ship Channel Watershed.

For the purpose of TMDL development, the project was subdivided into five subprojects: Greens Bayou Watershed, Halls Bayou Watershed, Brays Bayou Watershed, Sims Bayou Watershed, and Eastern Houston Watersheds. The Eastern Houston Watersheds project includes bacteria-impaired segments in the Houston Ship Channel and Houston Ship Channel/Buffalo Bayou watersheds. This TMDL report addresses the Halls Bayou Watershed.

1.1 Watershed Description

Halls Bayou, a tributary of Greens Bayou, is located in north central Harris County. The Halls Bayou Watershed drains an area of about 44 square miles and encompasses the City of Houston and incorporated areas of Harris County. The bayou runs east from Veterans Memorial Drive to Brock Park where it joins Greens Bayou (Harris County Flood Control District [HCFCD] 2008). There are about 74 miles of open streams within the watershed.

The watershed is primarily composed of developed urban land with a mix of residential, commercial, and industrial uses (HCFCD, 2008).

Subwatershed List

This report focuses on the following waterbodies/assessment units that TCEQ placed in Category 5 [303(d) List] of the 2008 Integrated Report for nonsupport of contact recreation use:

- Halls Bayou below U.S. 59, Assessment Unit 1006D_01
- Halls Bayou above U.S. 59, Assessment Unit 1006D_02
- Unnamed Tributary of Halls Bayou, Assessment Unit 1006I_01
- Unnamed Tributary of Halls Bayou, Assessment Unit 1006J_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 HCFCD. Using the TSARP GIS file results in watershed delineations that are slightly different than the historic delineations based on Texas Commission on Environmental Quality (TCEQ) GIS files associated with classified segments (Segment 1006). 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 (U.S. Army Corps of Engineers [USACE] 1985). The average daytime temperature in the summer 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 subtropical convection, winter rainfall by frontal storms, and fall and spring months by combinations of these two (Burian and Shepherd 2005). The 100-year floodplain encompasses about 20 percent of the drainage area of the watershed, approximately 9 square miles (HCFCD 2008).

Table 1-1, derived from the 2000 U.S. Census, summarizes the population for the City of Houston as well as for Harris County, as about half of the watershed lies on incorporated areas of Harris County (U.S. Census Bureau 2000). For comparison purposes, the 2010 estimated population from the Texas Water Development Board was included to show the population growth for the City of Houston and Harris County.

Table 1-1 City Population and Density

Name	2000 U.S. Census	2000 Population Density (per square mile)	Texas Water Development Board Projections 2010[a]	2010 Population Density (per square mile)
City of Houston	1,953,631	3,371	2,240,974	3,867
Harris County	3,400,578	1,967	3,590,782	2,077

[a] *Texas Water Development Board 2005*

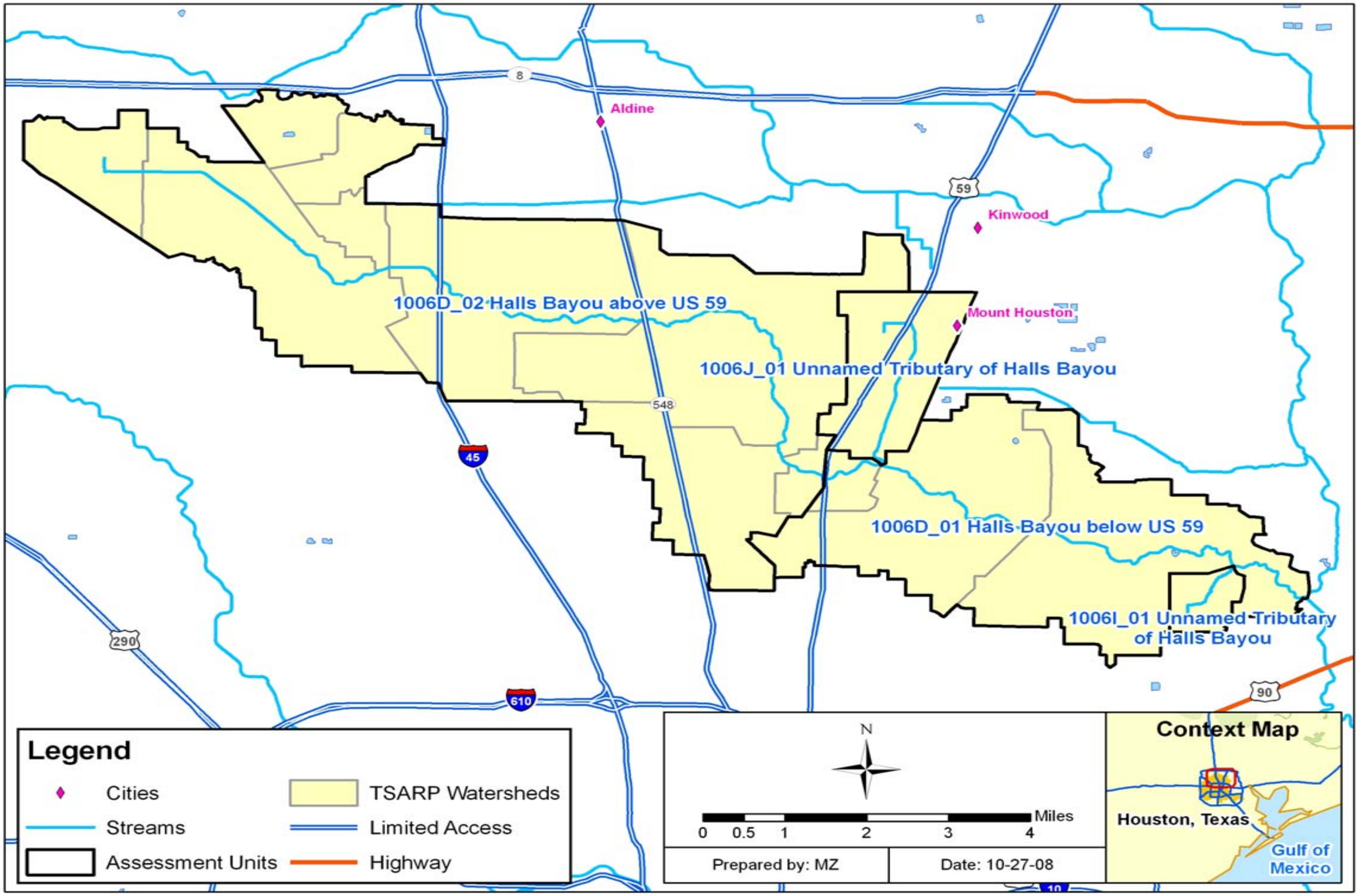


Figure 1-1 Location Map for Halls Bayou Watershed

1.2 Summary of Existing Data

The following subsections summarize existing data relevant to soil, land use, and precipitation throughout the watershed as well as the available ambient water quality and stream flow data for the Study Area.

1.2.1 Soil and Topography

The State Soil Geographic Database (STATSGO) (National Resources Conservation Service [NRCS] 1994) information was used to characterize soil in the Halls Bayou Watershed. As can be observed in Figure 1-2, the soil types that dominate the watershed are primarily from the Clodine soil series. Table 1-2 lists the distribution and attributes of the two soil series found in the Study Area.

Table 1-2 Characteristics of Soil Types within Halls Bayou Watershed

NRCS Soil Type	Soil Series Name	Percent of Watershed Area	Surface Texture	Hydrologic Group	Soil Drainage Class	Min Water Capacity (in/in)	Max Water Capacity (in/in)	Min Bulk Density (g/cm3)
TX100	Clodine	93.6%	Loam	D	Poorly Drained	0.15	0.15	1.4
TX007	Aldine	6.4%	Fine Sandy Loam	D	Somewhat Poorly Drained	0.13	0.18	1.45

Source: All data obtained/calculated from STATSGO database

The topography of the area is characteristic of the Texas Gulf Coastal Plains - flat, grassy, and mostly treeless (USACE 2005). Elevations in the watershed vary from about 111 feet near the headwaters to about 8 feet at the mouth of Halls Bayou, with a predominant slope of about 0.3%.

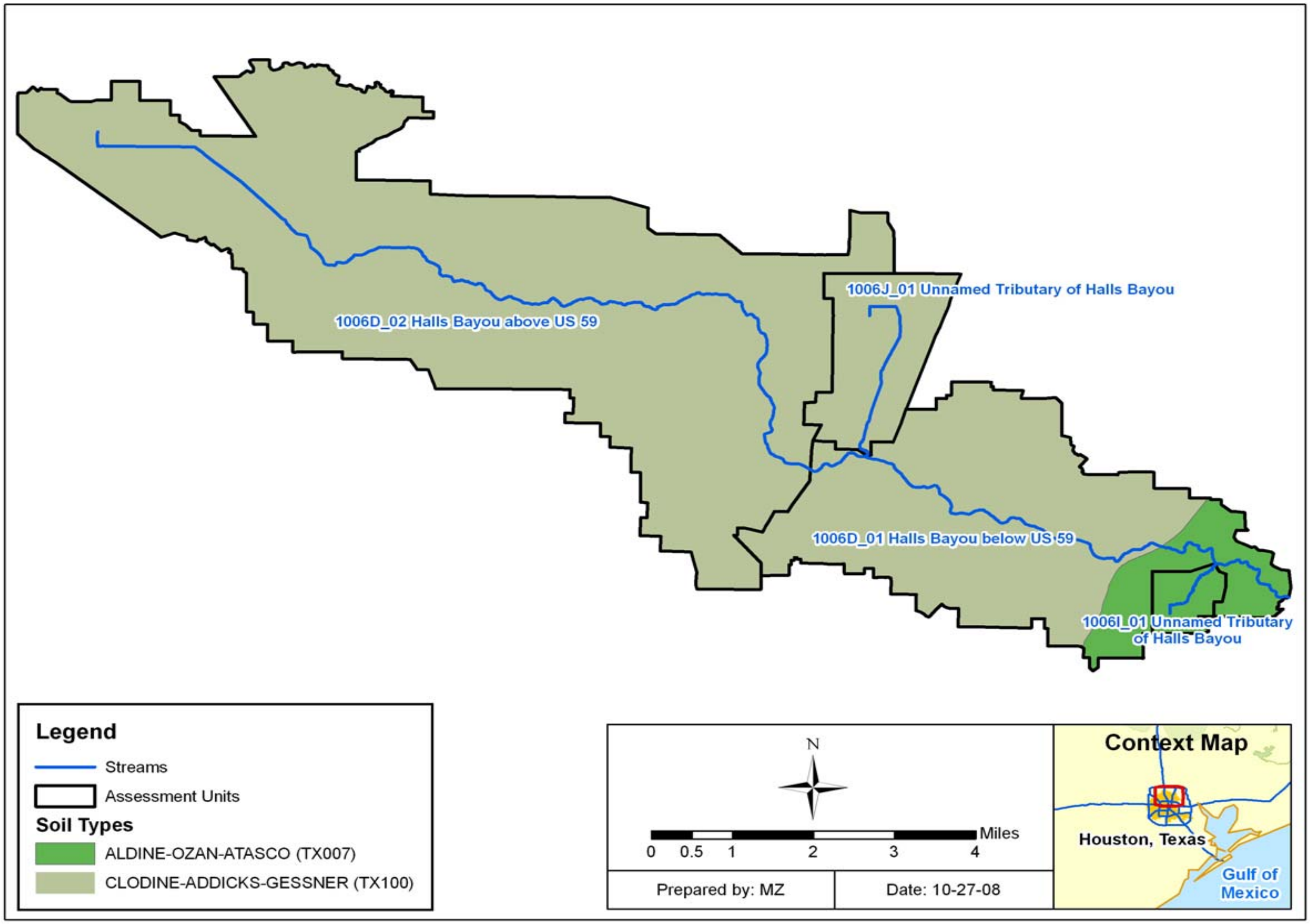


Figure 1-2 Halls Bayou Watershed Soil Types

1.2.2 Land Use

Most of the Halls Bayou Watershed is highly developed (79% for overall watershed), with an overall woodland contribution of 14 percent. Table 1-3 summarizes the acreages and the corresponding percentages of the land use categories for the contributing watershed associated with each respective assessment unit in the Study Area. The land use/land cover data were derived from the National Oceanic and Atmospheric Administration's (NOAA) Coastal Services Center. The specific land use/land cover data files were derived from the Coastal Change Analysis Program (C-CAP), Texas 2005 Land Cover Data (NOAA 2007). The land use categories are displayed in Figure 1-3. The total acreage of each segment in Table 1-3 corresponds to the watershed delineation in Figure 1-3. As mentioned before, the predominant land use category in this watershed is developed land (between 72.9% and 88.5%) followed by woody land (between 8.6% and 20.2%). Open water and bare/transitional land account for less than 2 percent of the subwatersheds.

Table 1-3 Aggregated Land Use Summaries by Segment

Aggregated Landuse Category	Segment Name and ID			
	Halls Bayou			
Assessment Unit	1006D_01	1006D_02	1006I_01	1006J_01
Percent Developed	72.9	80.4	77.5	88.5
Percent Cultivated Land	0	0	0	0
Percent Pasture/Hay	0.2	1.6	0	0
Percent Grassland/Herbaceous	0.8	2.9	0.1	0.3
Percent Woody Land	20.2	12.1	12.4	8.6
Percent Open Water	0.0	0.1	0.0	0.0
Percent Wetland	5.8	2.6	10.0	2.5
Percent Bare/Transitional	0.1	0.3	0	0.1
Acres of Developed	5,959	14,548	348	1,630
Acres Cultivated Land	0	0	0	0
Acres Pasture/Hay	13	284	0	0.0
Acres Grassland/Herbaceous	68	535	0	5
Acres of Woody Land	1,656	2,189	56	157
Acres of Open Water	2	13	0	2
Acres of Wetland	476	465	48	45
Acres of Bare/Transitional	9	56	0	0
Watershed Area (acres)	8,182	18,090	452	1,839

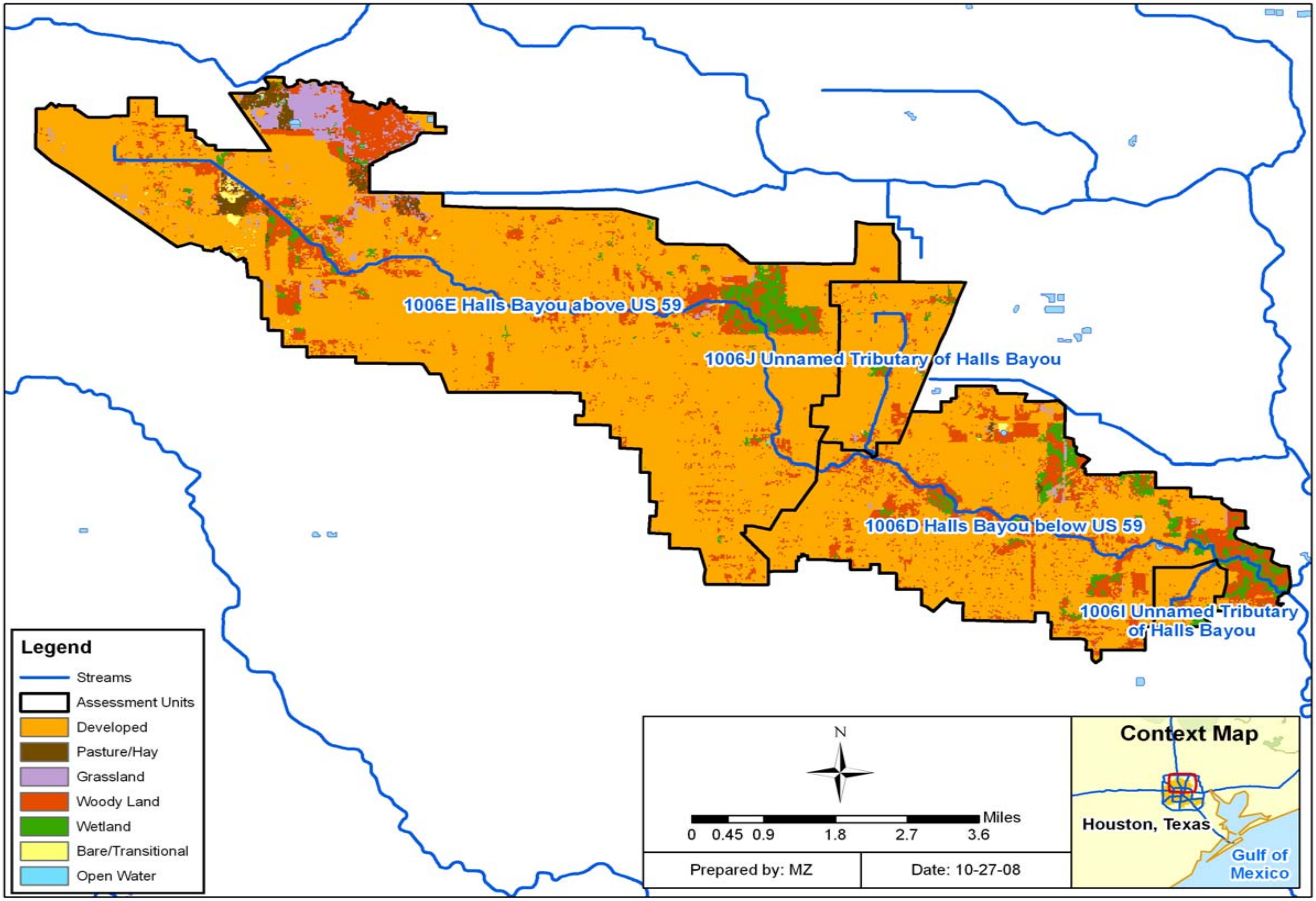


Figure 1-3 Land Use Map

1.2.3 Precipitation

There are three rain gages located within the watershed (Figure 1-4). The gages are maintained by the Harris County Office of Homeland Security and Emergency Management (HCOEM). Table 1-4 summarizes total annual rainfall for the three gages for a 20-year period. The Study Area has high levels of humidity and receives annual precipitation ranging between 23 and 76 inches per year (Table 1-4). Based on data for the period 1988 to 2007, the watershed average is around 48.8 inches per year. Figure 1-4 shows average annual rainfall across the Study Area. This grid was obtained by kriging data from 148 HCOEM rain gages located across Harris, Fort Bend, and Galveston Counties. Average values by subwatershed are summarized in Table 1-5. These average values were used to support the development of flow duration curves (Section 4).

Table 1-4 Annual Totals at Rainfall Gages in Halls Bayou Watershed (in inches)

Assessment Unit	Gage Number	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
1006D_02	1680	23.7	53.9	38.9	NA	67.3	58.3	43.3	38.4	36.1	72.1
1006D_02	1690	22.7	50.7	37.7	73.0	67.2	60.2	48.9	50.6	45.3	76.2
1006D_01	1675	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Assessment Unit	**Gage Number**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
1006D_02	1680	40.0	23.7	32.1	65.6	48.9	38.8	49.5	34.6	NA	57.4
1006D_02	1690	51.8	31.5	45.2	69.3	49.0	50.6	67.2	45.1	47.2	55.6
1006D_01	1675	NA	NA	NA	NA	57.9	NA	68.8	42.3	60.7	45.7

Average annual rainfall over period of 1988 to 2007 is 49.8 inches.

Table 1-5 Annual Average Precipitation in Halls Bayou Subwatersheds, 1988-2007 (in inches)

Assessment Unit	Average Annual (Inches)
1006D_01	55.1
1006D_02	45.7
1006I_01	55.1
1006J_01	45.7

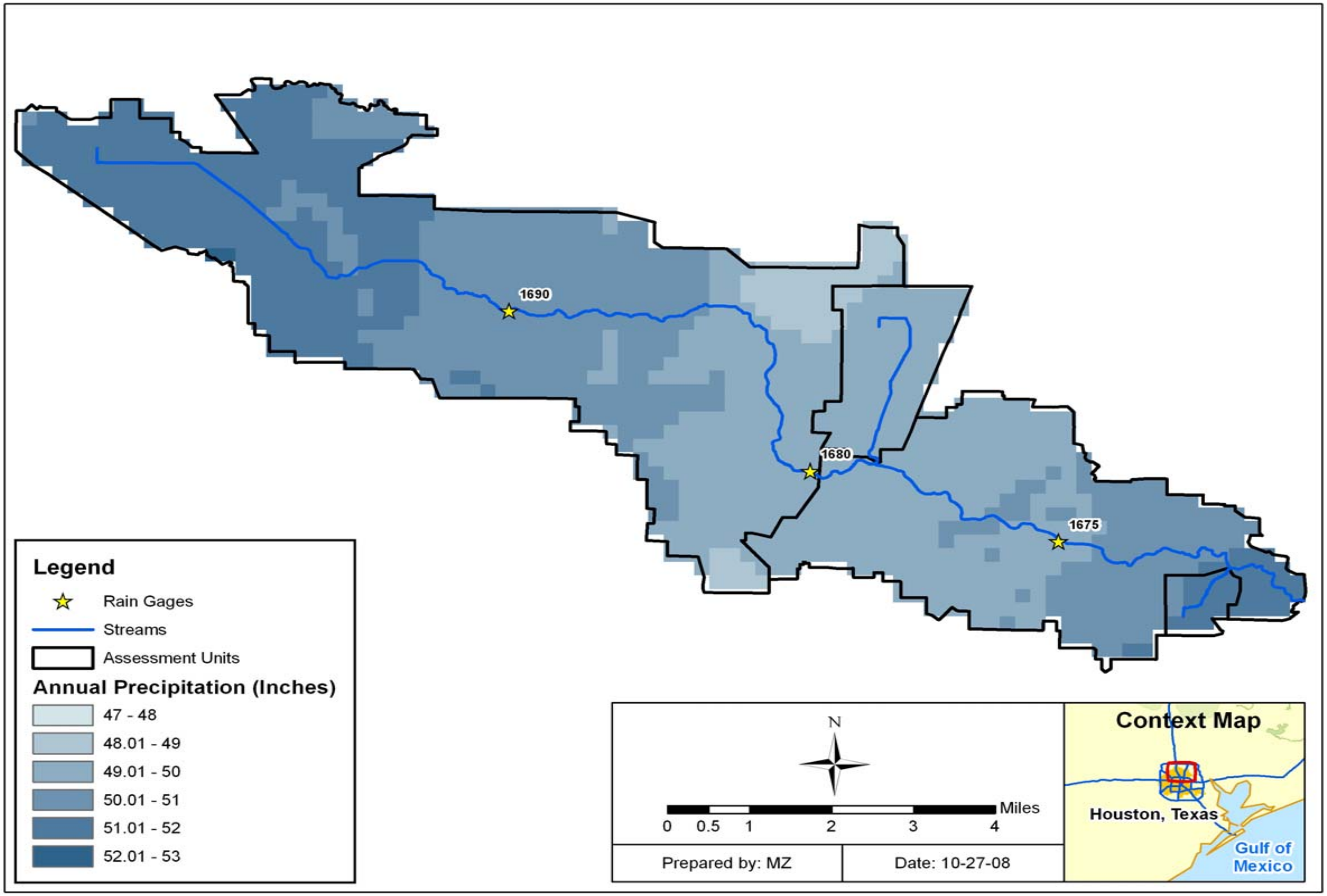


Figure 1-4 Precipitation Map

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 Halls Bayou Watershed. Historical indicator bacteria data for the period 1992 to 2008 were obtained from the TCEQ SWQMIS database, which includes results from the sampling events conducted under this project in 2006. Fifty-one percent of the data correspond to *E. coli* concentrations (704 samples), while the remaining 49 percent correspond to fecal coliform concentrations (671 samples).

Table 1-6 summarizes the historical ambient water quality data for indicator bacteria (1992-2008) for select TCEQ Water Quality Monitoring (WQM) stations in the Halls Bayou Watershed. Data in Table 1-6 collected prior to 2001 correspond to fecal coliform concentrations, while data for 2001-2008 are primarily *E. coli* concentrations. Figure 1-5 shows the locations of the WQM locations with indicator bacteria data. The complete ambient water quality dataset for bacteria used to prepare Table 1-6 is provided in Appendix A. Table 1-6 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 dataset is provided in Subsections 2.3 and 2.4.

Table 1-6 Historical Water Quality Data for TCEQ Stations from November 1992 to March 2008

Segment	Assessment Unit	WQM Station ID	Indicator Bacteria	Geometric Mean Criteria	Geometric Mean Concentration	Single Sample Criteria	Number of Samples	Number of Samples Exceeding Single Sample Criteria	% of Samples Exceeding
1006D	1006D_01	11127	EC	126	1406	394	57	42	74%
			FC	200	932	400	77	51	66%
		15862	EC	126	1252	394	57	39	68%
			FC	200	765	400	40	25	63%
		15863	EC	126	1358	394	57	45	79%
			FC	200	2140	400	50	45	90%
		15864	EC	126	821	394	84	56	67%
			FC	200	1415	400	40	33	83%
		20023	EC	126	916	394	17	10	59%
	1006D_02	11126	EC	126	1953	394	53	44	83%
			FC	200	1596	400	194	155	80%
		17490	EC	126	3443	394	54	50	93%
		17491	EC	126	601	394	53	34	64%
1006I	1006I_01	16666	EC	126	1122	394	71	56	79%
			FC	200	1869	400	78	59	76%
		16667	EC	126	664	394	57	33	58%
			FC	200	719	400	77	50	65%
1006J	1006J_01	16665	EC	126	1816	394	75	65	87%
			FC	200	1555	400	78	67	86%

EC: E. coli in MPN/100mL
FC: Fecal Coliform in cfu/100mL

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) operates flow gages at one location on Halls Bayou to measure flow and elevations. The period of record and type of data collected are listed in Table 1-7. The location of the gage is shown on Figure 1-5. The historical flow data available from this gage are included in Appendix B.

Table 1-7 USGS Gages in the Halls Bayou Watershed

USGS Gage Number	Name	Period of Record	Data Type
8076500	Halls Bayou at Houston, TX	11/1952 – 09/1993 and 10/2000 - Present	Discharge (cfs)
		10/1996 - Present	Gage Height (ft)

During intensive surveys conducted in the summer of 2006, instantaneous flow was measured at three WQM stations within the Study Area: 20023 (assessment unit 1006D_01), 16666 (assessment unit 1006I_01), and 16665 (assessment unit 1006J_01). The complete set of instantaneous flow data is also provided in Appendix B. A few historical measurements were available from the SWQMIS database to assist in characterizing flows (Appendix B).

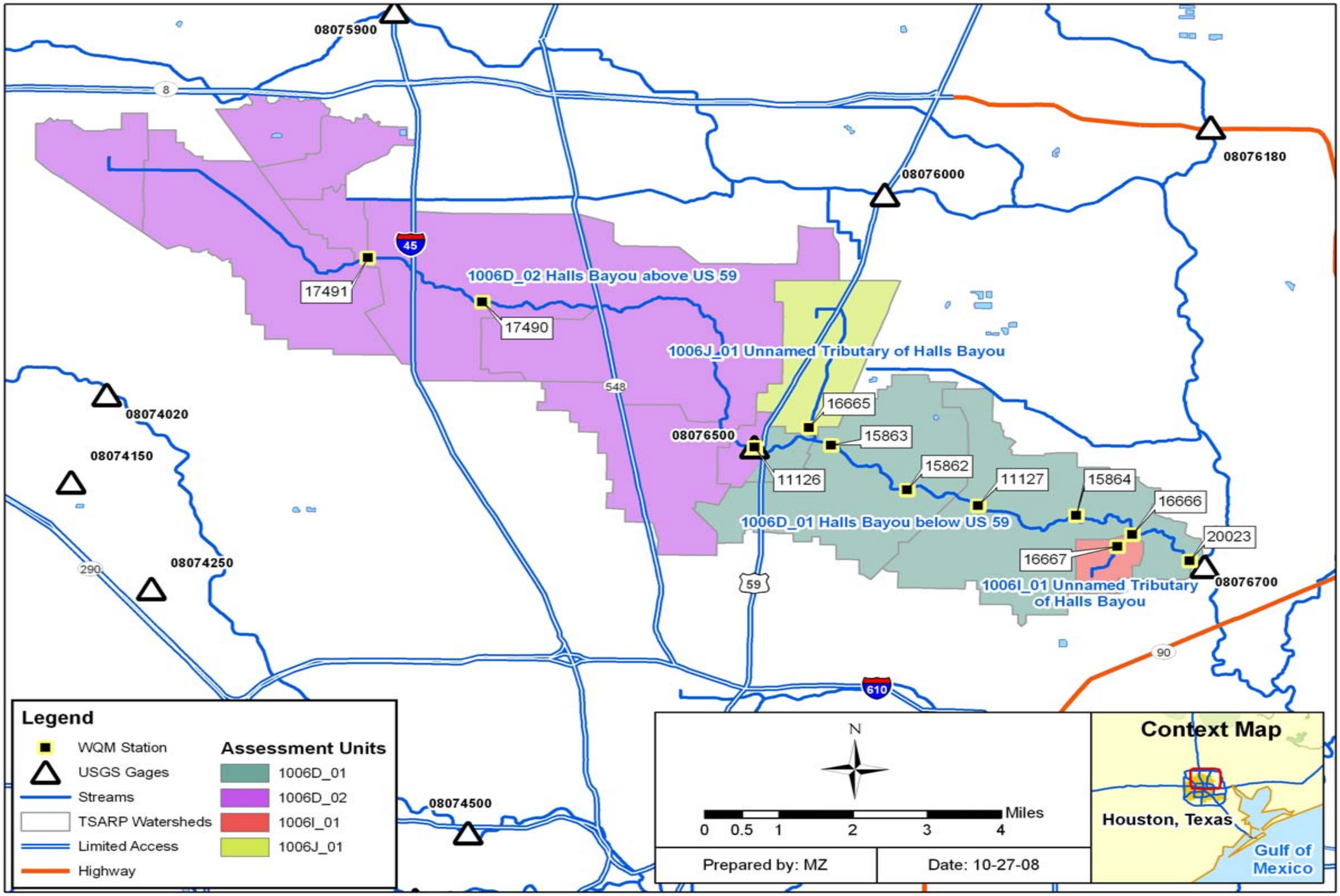


Figure 1-5 WQM and USGS Station Locations

1.3 Halls 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 1-8) and the following criteria: warm temperatures ranged from 24 – 32°C and cool temperatures ranged from 12 – 18°C were used to divide the data sets into warmer and cooler months. Based on this, November, December, January, and February were cooler months, and May, June, July, August, and September were warmer months.

Table 1-8 Average Monthly Temperatures for Houston Hobby AP, TX (1971-2000)

Month	Daily Max (°C)	Daily Min (°C)	Daily Mean (°C)	Classification
Jan	17.4	7.3	12.4	Cool
Feb	19.5	9	14.3	Cool
Mar	23.1	12.7	17.9	
Apr	26.3	15.9	21.1	
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	
Nov	22.5	11.9	17.2	Cool
Dec	18.6	8.2	13.4	Cool

Note: Temperature values from NOAA (degrees Fahrenheit) have been converted to degrees Celsius.
http://cdo.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl

A t-test was conducted on log transformed data between the warmer months and cooler months for stations with 6 or more samples. Geometric means were also calculated for the warmer and cooler months. Table 1-9 shows that 3 out of 8 stations (37%) exhibited higher geometric means for colder months than for warmer months, but only at one station was the cool geomean significantly higher (p-value<0.05) than the warm geomean. Overall there was no seasonal significant difference in fecal coliform data.

Table 1-9 Seasonal Differences for Fecal Coliform Concentrations

Assessment Unit	Station ID	Warm Months		Cool Months		*p*-value
		n	Geomean (cfu/100mL)	n	Geomean (cfu/100mL)	
1006D_01	11127	36	585	20	340	0.388
	15862	14	354	12	716	0.196
	15863	19	1,427	14	1,567	0.845
	15864	14	1,792	12	577	0.124
1006D_02	11126	82	1,917	86	676	0.0001
1006I_01	16666	33	2,863	23	1,454	0.222
	16667	32	853	23	347	0.114
1006J_01	16665	32	1,052	23	2,674	0.036

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 cfu/100mL.

For *E. coli*, Table 1-10 shows that 70 percent of the stations (7 out of 10) exhibited higher geometric mean concentrations for the colder months than the warmer months. However, there is not statistically significant difference (*p*-value = 0.05) between the cool and the warm datasets.

Table 1-10 Seasonal Differences for *E. coli* Concentrations

Assessment Unit	Station ID	Warm Months		Cool Months		*p*-value
		n	Geomean (MPN/100mL)	n	Geomean (MPN/100mL)	
1006D_01	11127	21	1,055	26	2,379	0.162
	15862	22	945	25	2,090	0.112
	15863	22	1,810	26	1,243	0.471
	15864	38	706	39	1,228	0.216
	20023	17	916	0	-	NA
1006D_02	11126	22	1,843	26	1,656	0.852
	17490	22	3,896	22	2,741	0.491
	17491	22	530	22	788	0.535
1006I_01	16666	39	1,057	26	1,959	0.177
	16667	22	554	25	844	0.366
1006J_01	16665	41	1,467	26	2,859	0.072

n = number of samples; ; NA = not available. Test could not be conducted because station does not have data for cool months.
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 MPN/100mL.

Overall this analysis of fecal coliform and *E. coli* data demonstrates that there is no significant difference in indicator bacteria between cool and warm weather seasons.

SECTION 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 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 the indicator of the potential presence of fecal contamination (USEPA 1986). The USEPA-recommended criterion for recreational waters in 1976 included a geometric mean criterion: no more than 200 cfu/100mL 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 cfu/100mL (USEPA 1986). Shortly thereafter this recommended criterion was adopted by the State of Texas in its SWQS. These 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. As a result, USEPA recommended new criteria for swimming areas, using *E. coli* as the new fecal indicator organism, and incorporating the idea of varying criteria with the level of swimming use. TCEQ then revised the WQS in 2000 to establish *E. coli* as the new indicator bacteria for assessment of contact recreation in all freshwater.

Thus in Texas both indicator bacteria - fecal coliform and *E. coli* - can be used to determine support of the contact recreation use in freshwater. However, it is expected that over time since only *E. coli* bacteria are measured through the statewide ambient monitoring program to determine the relative risk of contact recreation, reliance on fecal coliform data will diminish. The presence of *E. coli* indicates that associated pathogens from the waste of warm-blooded species (human or animal) may be reaching a body of water. The standard associated with contact recreation use is designed to ensure that water is safe for swimming, wading by children, or other water sports that involve direct contact with the water, especially with the possibility of ingesting it. High concentrations of certain indicator bacteria in water indicate there may be a risk of becoming ill from recreational activities.

Texas WQSs 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.*, Houston Ship Channel), unrelated to water quality. This exemption and reclassification to less strict “noncontact recreation” standards have 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 the waterbodies within the Halls Bayou Watershed identified on the §303(d) List of the 2008 Texas Water Quality Inventory because they do not support contact recreation use. Table 2-1 summarizes the designated uses and the applicable indicator bacteria 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 §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. TMDLs are a necessary step in the process to restore contact recreation use for each waterbody.

Table 2-1 Synopsis of Texas Integrated Report for Waterbodies in the Halls Bayou Watershed

Segment ID	Segment Name	Assessment Unit	Indicator Bacteria	Designated Use*				Year Placed on 303(d) List	Stream Length (miles)
				CR	AL	GU	FC		
1006D	Halls Bayou below U.S. 59	1006D_01	*E. coli* (or fecal coliform)	NS	S	S	NA	2002	8.3
	Halls Bayou above U.S. 59	1006D_02	*E. coli* (or fecal coliform)	NS	S	S	NA	2002	11.1
1006I	Unnamed Tributary of Halls Bayou	1006I_01	*E. coli* (or fecal coliform)	NS	S	S	NA	2004	0.7
1006J	Unnamed Tributary of Halls Bayou	1006J_01	*E. coli* (or fecal coliform)	NS	S	S	NA	2002	2.0

**CR: Contact recreation*
AL: Aquatic Life
GU: General Use
FC: Fish Consumption
NS: Nonsupport
S = Support
NA = not available, the 2006 Texas Water Quality Inventory does not state level of support for this designated use

The excerpts below from Chapter 307, SWQS (TCEQ 2000) stipulate how water quality data were assessed to determine support of the 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 Halls 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, wasteload 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 (TCEQ 2000).

§307.7. Site-specific Uses and Criteria.

(a) Uses and numerical criteria are established on a site-specific basis in Appendices A, D, and E of §307.10 of this title (relating to Appendices A - E). 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 the activities of man. 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 two categories - contact recreation waters and noncontact recreation waters. Classified segments are designated for contact recreation unless elevated concentrations of indicator bacteria frequently occur due to sources of pollution which cannot be reasonably controlled by existing regulations or 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 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 "colony forming units" of bacteria per 100 milliliters (mL) of water. Even where the concentration of indicator bacteria is less than the criteria for 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 latest approved version of the TNRCC Guidance for Screening and Assessing Texas Surface and Finished Drinking Water Quality Data.

(A) Freshwater

(i) Contact recreation. The geometric mean of E. coli should not exceed 126 per 100 mL. In addition, single samples of E. coli should not exceed 394 per 100 mL. Contact recreation applies to all bodies of freshwater except where specifically designated otherwise in §307.10 of this title (relating to Appendices A - E).

(ii) Noncontact recreation. The geometric mean of E. coli should not exceed 605 per 100 mL.

(B) Saltwater

(i) Contact recreation. The geometric mean of Enterococci should not exceed 35 per 100 mL. In addition, single samples of Enterococci should not exceed 89 per 100 mL. Contact recreation applies to all bodies of saltwater, except where specifically designated otherwise in §307.10 of this title.

(ii) Noncontact recreation. The geometric mean of Enterococci should not exceed 168 per 100 mL.

(C) Fecal coliform bacteria. Fecal coliform bacteria can be used as an alternative instream indicator of recreational suitability until sufficient data are available for E coli or Enterococci. For segments designated as oyster waters in §307.10 of this title, fecal coliform can continue to be used as an indicator of recreational suitability because fecal coliform is used as the indicator for suitability of oyster water use as described in paragraph (3)(B) of this subsection. Fecal coliform can also continue to be used as a surrogate indicator in effluent limits for wastewater discharges. Fecal coliform criteria are the same for both freshwater and saltwater, as follows.

(i) Contact recreation. The geometric mean of fecal coliform should not exceed 200 per 100 mL. In addition, single samples of fecal coliform should not exceed 400 per 100 mL.

(ii) Noncontact recreation. Fecal coliform shall not exceed 2,000 per 100 mL as a geometric mean. In addition, single samples of fecal coliform should not exceed 4,000 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 EPA 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.

§307.10. Appendices A - E.

The indicator bacteria for recreation for freshwater is E. coli and for saltwater is Enterococci. Fecal coliform can still be used as an alternative indicator during the transition to the new indicator bacteria, as specified in §307.7 (b). The appropriate bacterial criteria and fecal coliform alternative are listed in the appendix under the Indicator Bacteria column. E. coli criteria of 126 colonies per 100 mL of water are applied as specified in §307.7(b)(1)(A)(i) and (ii) for contact recreation (relating to Site-specific Uses and Criteria). The criteria of 605 colonies per 100 mL of water are applied as specified in §307.7(b)(1)(A)(iii) for noncontact recreation. Enterococci criteria of 35 colonies per 100 mL are applied as specified in §307.7(b)(1)(B)(i) and (ii) for contact recreation, and 168 colonies per 100 mL for noncontact recreation. The indicator bacteria for suitability for oyster waters is fecal coliform. The fecal coliform criteria for oyster waters is 14 colonies per 100 mL as specified in §307.7(b)(3)(B).

As an alternative, fecal coliform criteria of 200 per 100 mL are applied as specified in §307.7(b)(1)(C)(i) and (ii). Fecal coliform criteria of 2,000 per 100 mL are applied as specified in §307.7(b)(1)(C)(iii).

As stipulated in Draft 2006 *Guidance for Assessing and Reporting Surface Water Quality in Texas* (TCEQ 2007), utilization of the geometric mean to determine compliance for any of the bacterial indicators depends on the collection of at least 10 samples over the most recent 10-year period.

Draft 2006 Guidance for Assessing and Reporting Surface Water Quality in Texas (TCEQ 2007):

- *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 2006 assessment period of record for the last five years is December 1, 1999 through November 30, 2004. Samples from these five years are evaluated when available, if necessary, the most recent samples collected in the preceding five years (December 1, 1994 through November 30, 1999) can also be included to meet the requirements for minimum sample number.*

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 2008 Texas Water Quality Inventory and §303(d) List (TCEQ 2008). Between 1996 and 2008 the TCEQ WQSs and water quality assessment method were modified and additional water quality data were collected throughout the Halls Bayou Watershed. As a result various tributaries of Halls Bayou were added to the §303(d) List over this time frame. All the waterbodies listed in Table 2-2 are recognized as Category 5a and, as such, are considered high priority for TMDL development. 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 locations of these WQM stations are displayed in the map included as Figure 1-5. The waterbodies requiring the TMDLs were first listed in 2002. Water quality data from 1996 through 2000 were used by TCEQ for the 2002 assessment. For the 2006 assessment, the data from December 1, 1999 through November 30, 2004 were used for the assessment of contact recreation use.

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

Assessment Unit	Water Body	Description of Assessment Unit Not Supporting Contact Recreation Use	Monitoring Station IDs	Assessment Year
1006D_01	Halls Bayou below U.S. 59	Halls Bayou 1 mile upstream of Confluence w/ Greens Bayou (downstream of Station 16666)	20023	2002
1006D_02	Halls Bayou above U.S. 59	Halls Bayou at Jensen Dr. in Houston	11126	2002
1006I_01	Unnamed Tributary of Halls Bayou	Trib of Halls at Talton Dr. near Monterrey Ln.	16666	2002
1006J_01	Unnamed Tributary of Halls Bayou	Trib of Halls Bayou at Langley Road in North Houston	16665	2002

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 use 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;
- TCEQ policy and procedures from other TCEQ/U.S. Environmental Protection Agency (USEPA)- approved bacteria TMDLs in Texas;
- refinements in the TCEQ surface water quality monitoring procedures; and
- 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, only a portion of the historical data set was used to support the TMDLs in this report.

Table 2-3 summarizes the portion of the historical ambient water quality data set from the TCEQ WQM stations in each impaired assessment unit. Only indicator bacteria data from 1999 to September 2006 were used in Table 2-3 for TMDL development to adhere to TCEQ assessment guidelines and to correspond to the available period of record used to estimate stream flows and existing wastewater treatment plant flows. From the data results in Table 2-3, key inferences can be made regarding the temporal and spatial extent of the contact recreation use impairment.

Table 2-3 Water Quality Data for TCEQ WQM Stations from 1996 to 2006

Segment	Assessment Unit	WQM Station ID	Indicator Bacteria	Geometric Mean Criteria	Geometric Mean Concentration	Single Sample Criteria	Number of Samples	Number of Samples Exceeding Single Sample Criteria	% of Samples Exceeding
1006D	1006D_01	11127	EC	126	1406	394	57	42	74%
			FC	200	707	400	82	51	62%
		15862	EC	126	1252	394	57	39	68%
			FC	200	765	400	40	25	63%
		15863	EC	126	1248	394	58	45	78%
			FC	200	2140	400	50	45	90%
		15864	EC	126	854	394	85	57	67%
			FC	200	1415	400	40	33	83%
		20023	EC	126	916	394	17	10	59%
	1006D_02	11126	EC	126	1545	394	58	46	79%
			FC	200	1477	400	197	155	79%
		17490	EC	126	3443	394	54	50	93%
		17491	EC	126	557	394	54	34	63%

Segment	Assessment Unit	WQM Station ID	Indicator Bacteria	Geometric Mean Criteria	Geometric Mean Concentration	Single Sample Criteria	Number of Samples	Number of Samples Exceeding Single Sample Criteria	% of Samples Exceeding
1006I	1006I_01	16666	EC	126	1141	394	75	59	79%
			FC	200	2041	400	80	61	76%
		16667	EC	126	664	394	57	33	58%
			FC	200	829	400	79	52	66%
1006J	1006J_01	16665	EC	126	1780	394	77	67	87%
			FC	200	1653	400	79	68	86%

EC: E. coli in MPN/100mL
FC: Fecal Coliform in cfu/100mL
Highlight indicates downstream WQM station selected for TMDL development and indicator bacteria selected as target parameter.

Halls Bayou below U.S. 59 (Assessment Unit 1006D_01): At all the WQM stations with fecal indicator data (five total), more than 25 percent of the samples exceed the single sample criteria for *E. coli* and fecal coliform, and the geometric mean criteria were also exceeded. This indicates conditions of widespread and persistent elevated levels of bacteria resulting in nonsupport of contact recreation use.

Halls Bayou above U.S. 59 (Assessment Unit 1006D_02): At the three WQM stations, more than 25 percent of the samples exceed the *E. coli* and fecal coliform criteria, and the geometric mean criteria were exceeded as well. Data, therefore, show conditions of widespread and persistent elevated levels of bacteria resulting in nonsupport of contact recreation use.

Unnamed Tributary of Halls Bayou (Assessment Unit 1006I_01): Both the single sample and geometric mean criteria for *E. coli* and fecal coliform were exceeded at the two WQM stations. Available data, thus, demonstrate persistent elevated levels of bacteria resulting in nonsupport of contact recreation use.

Unnamed Tributary of Halls Bayou (Assessment Unit 1006J_01): At the only WQM station 16665, more than 25 percent of the samples exceed the *E. coli* and fecal coliform criteria established for this waterbody, and the geometric mean criteria were also exceeded. Given the small size of this subwatershed, this station adequately represents water quality conditions throughout the segment and the available data demonstrates persistent elevated levels of bacteria resulting in nonsupport of contact recreation use.

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 2000) 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 2000 Texas SWQSs as described in Subsection 2.2 above. *E. coli* is the preferred indicator bacteria for assessing contact recreation use in freshwater but fecal coliform bacteria may also be used since it was the preferred indicator in the past.

Several studies performed by the USEPA show a stronger link between the concentrations of *E. coli* 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 394 MPN/100mL for single samples of *E. coli* and a geometric mean limit of 126 MPN/100mL for waterbodies designated for contact recreation use. During the process of switching to the new standards, the USEPA recommended that fecal coliform concentrations (400 cfu/100mL in any single sample and 200 cfu/100mL for the geomean of all samples) be used until at least 10 data points have been collected for *E. coli* for each segment.

The water quality target for the TMDLs for freshwater segments is to maintain concentrations below the geometric mean criterion of 126 MPN/100mL for *E. coli* or if necessary, 200 cfu/100mL for fecal coliform. 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 attainment of the contact recreation use. TMDLs will be based on a percent reduction goal required to meet the geometric mean criterion.

The stations highlighted in Table 2-3 correspond to the specific WQM stations where TMDLs will be set for the Halls Bayou Watershed. The assessment units for which TMDLs will be developed are shown in Figure 2-1. For all the segments in the Study Area, *E. coli* is the selected indicator bacteria.

The water quality target for each waterbody will incorporate an explicit 5 percent margin of safety (MOS). Thus, for *E. coli* the single sample water quality target would be 374 MPN/100mL, 5 percent lower than the criterion value (394 MPN/100mL), and the geometric mean water quality target would be 120 MPN/100mL, 5 percent lower than the criterion value (126 MPN/100mL).

TMDLs must take into account that no more than 25 percent of the samples may exceed the single sample numeric criterion. However, TMDLs will be based on a percent reduction goal required to meet the geometric mean criteria.

Each water quality target will be used to determine the allowable bacteria load derived by using the actual or estimated flow record multiplied by the instream criteria minus a 5 percent MOS. The line drawn through the allowable load data points is the water quality target that represents the maximum load for any given flow and still satisfies the WQS.

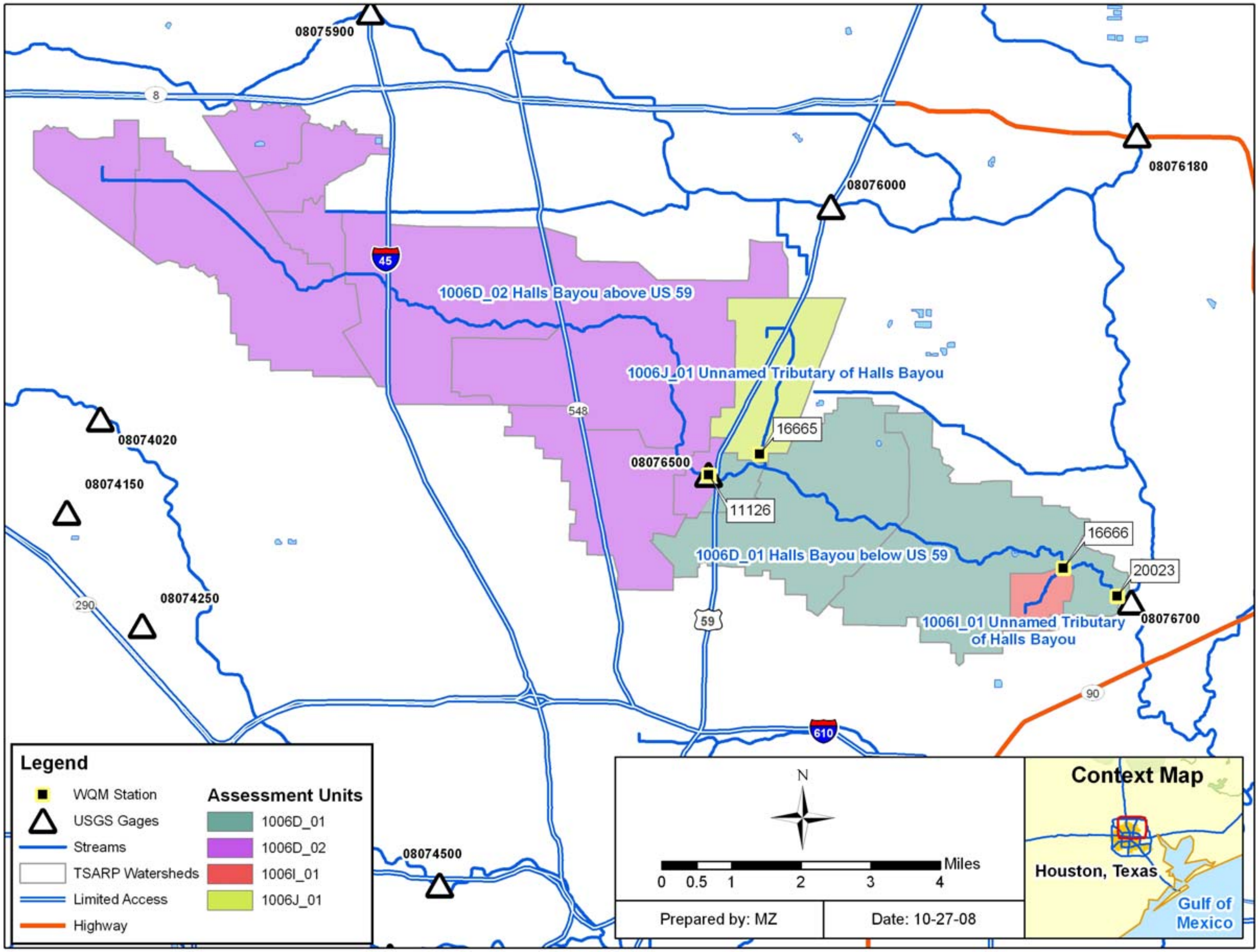


Figure 2-1 TMDL Station Locations

SECTION 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* originate in the intestines of warm-blooded species (human and animal), and sources of bacteria may be point (permitted) or nonpoint (non-permitted) in nature.

Point sources are permitted through the National Pollution Discharge Elimination System (NPDES) program. Some storm water runoff may be permitted through NPDES as municipal separate storm sewer systems (MS4). Other non-permitted sources of storm water 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, non-permitted 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 in this report, all sources of pollutant loading not regulated by a NPDES-permit are considered nonpoint sources. The following discussion describes what is known regarding permitted and non-permitted 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 discernable, 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;
- TPDES municipal no-discharge WWTF;
- TPDES regulated storm water (construction, industrial and municipal storm sewer systems); and
- TPDES Concentrated Animal Feeding Operation (CAFO).

Continuous point source discharges such as WWTFs, could result in discharge of elevated concentrations of fecal bacteria if the disinfection unit is not properly maintained, is of poor design, or if flow rates exceed the disinfection capacity. Some industrial WWTF 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 storm water runoff from TPDES regulated discharge areas called municipal separate storm sewer systems can also contain high fecal bacteria concentrations. CAFOs are recognized by USEPA as significant sources of pollution, and may have the potential to cause serious impacts to water quality if not properly managed.

Watersheds in the Study Area, including Halls Bayou below U.S. 59 (1006D_01), Halls Bayou above U.S. 59 (1006D_02), and Unnamed Tributary of Halls Bayou (1006J_01) have NPDES/TPDES-permitted sources. However, there are no NPDES/TPDES-permitted sources located within Unnamed Tributary of Halls Bayou (1006I_01). Virtually, the entire Study Area (approximately 99%) is regulated under the TPDES storm water 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: Continuous Point Source Discharges

There are 49 permitted outfalls for WWTFs in the Study Area. The names and permit numbers of the TPDES-permitted facilities that continuously discharge wastewater to surface waters addressed in these TMDLs are listed in Table 3-1. Facility locations are displayed in Figure 3-1. A complete dataset of self-reported flows is included in Appendix C.

Not all TPDES-permitted facilities that discharge treated wastewater are required to monitor for fecal bacteria. In addition, while current instream water quality criteria are based on *E. coli* bacteria, permit limits are based on levels of fecal coliform, another measure of fecal bacteria of which *E. coli* is often the major constituent. Therefore, data on bacteria loads from WWTF outfalls are not available for all of the TPDES permitted dischargers in the Halls Bayou Watershed and only fecal coliform (not *E. coli*) concentrations are reported. Table 3-2 summarizes data from Discharge Monitoring Reports (DMR) available for three TPDES WWTFs that monitor their discharge for fecal coliform. The 90^{th} percentile of the monthly average load and the maximum monthly average loads are provided to estimate fecal coliform loads from these three TPDES WWTFs. The data used to generate Table 3-2 are provided in Appendix D. Table 3-2 also lists the number of reported monthly exceedances of the geometric mean concentration of 200 cfu/100mL, and the number of reported daily exceedances of the single sample standard of 400 cfu/100mL. As shown in Table 3-2, one of the permitted facilities exceeded fecal coliform permit limits during the monitoring time frame.

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

Segment	Stream Name	Assessment Unit	TPDES Number	NPDES NUMBER	Permittee Name	Facility Name	SIC	Facility Type	DTYPE	County	2008 Permitted Flow (MGD)	Average Monthly Flow (MGD)
1006D	Halls Bayou below US 59	1006D_01	12996-001	TX0096679	Aqua Utilities Inc	Redwood WWTP	4952	Sewerage Systems	D	HARRIS	0.1	0.041
		1006D_01	10495-016	TX0063053	City of Houston	Fwsd 23 WWTP	4952	Sewerage Systems	W	HARRIS	7	3.780
		1006D_01	10495-016	TX0063053	City of Houston	Fwsd 23 WWTP	4952	Sewerage Systems	W	HARRIS	7*	3.780*
1006D	Halls Bayou below US 59	1006D_02	01536-000	TX0007650	Ashbrook Simon-Hartley Opera	Ashbrook Houston Plant	3561	Pumps and Pumping Equipment	W	HARRIS	0.004	0.002
		1006D_02	10236-001	TX0021253	Sunbelt FWSD	Oakwilde WWTP	4941	Water Supply	D	HARRIS	0.45	0.310
		1006D_02	10419-001	TX0070611	Nitsch And Son Utility Company	Durkee Manor Plant	4952	Sewerage Systems	D	HARRIS	0.25	0.124
		1006D_02	10436-001	TX0032093	Champs Water Company	Western Homes Subdivision	4952	Sewerage Systems	D	HARRIS	0.15	0.086
		1006D_02	10495-151	TX0075663	City Of Houston	Willow Run WWTP	4952	Sewerage Systems	D	HARRIS	0.75	0.342
		1006D_02	10518-001	TX0021261	Sunbelt Fwsd	Sunbelt Fwsd WWTP	4952	Sewerage Systems	D	HARRIS	0.45	0.258
		1006D_02	10610-001	TX0030988	Southern Water Corp	Hidden Valley WWTP	4952	Sewerage Systems	D	HARRIS	0.475	0.345
		1006D_02	10679-001	TX0023825	Harris County WCID 74	Harris County WCID 74 WWTP	4952	Sewerage Systems	D	HARRIS	0.95	0.609
		1006D_02	10812-001	TX0021270	Sunbelt FWSD	High Meadows WWTP	4941	Water Supply	D	HARRIS	0.99	0.655
		1006D_02	10825-001	TX0032255	Harvest Communities of Houston	Aldine Community Care Center	8051	Skilled Nursing Care	D	HARRIS	0.023	0.007
		1006D_02	11154-001	TX0023515	Mount Houston Road MUD	Mount Houston Road MUD WWTP	4952	Sewerage Systems	D	HARRIS	0.95	0.135
		1006D_02	11231-001	TX0021245	Sunbelt FWSD	Heather Glen Wwtp	4952	Sewerage Systems	D	HARRIS	0.5	0.291
		1006D_02	11255-001	TX0032034	Texas-American Water Company	Greenwood Village WWTP	4952	Sewerage Systems	D	HARRIS	0.393	0.186
		1006D_02	11473-001	TX0066478	Blue Bell Manor Utility Co Inc	Blue Bell Manor Utility	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.6	0.365
		1006D_02	11673-001	TX0063860	Woodloch MHP LLC	Woodloch MHP WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.03	0.009
		1006D_02	11807-001	TX0071820	Forest Hills Mud	Forest Hills Mud Wwtp	4952	Sewerage Systems	D	HARRIS	0.8	0.117
		1006D_02	11821-001	TX0072184	Johnson, Ana Araujo	The Heavens Mobile Home Park	4952	Sewerage Systems	D	HARRIS	0.05	0.001
		1006D_02	12070-004	TX0100323	Aldine ISD	Aldine ISD Orange Grove WWTP	4952	Sewerage Systems	D	HARRIS	0.015	0.007
		1006D_02	12083-001	TX0078883	Hooks Mobile Home Park Ltd	Hooks MHP WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.06	0.027
		1006D_02	12259-001	TX0084531	Bayou Forest Village Inc	Bayou Forest Village WWTP	4952	Sewerage Systems	D	HARRIS	0.03	0.005
		1006D_02	12261-001	TX0084671	Solhjou Houshang	Melrose MHP WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.04	0.009
		1006D_02	12261-002	TX0119610	Solhjou Houshang	Pin Oak MHP WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.03	0.012
		1006D_02	12399-001	TX0087785	Karbalai Laura Redow	Sundown MHP WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.05	0.015
		1006D_02	12414-001	TX0088102	Woodgate Mobile Home Village	Woodgate Mobile Home Village	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.035	0.016
		1006D_02	12555-001	TX0090492	Westfield Mobile Home Commun	Westfield Mobile Home Park	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.1	0.065
		1006D_02	12882-001	TX0094986	Solhjou Bahram	Rosewood MHP WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.03	0.012
		1006D_02	12917-001	TX0095516	Hartzog Jr, William Emmett	Lone Willow MHP West WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.006	0.003
		1006D_02	12918-001	TX0095508	Hartzog Linda Dianne	Lone Willow MHP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.006	0.002
		1006D_02	13084-001	TX0097527	Mcculloch, Xiu Hui Li	Hartwick Green MHP WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.025	0.011

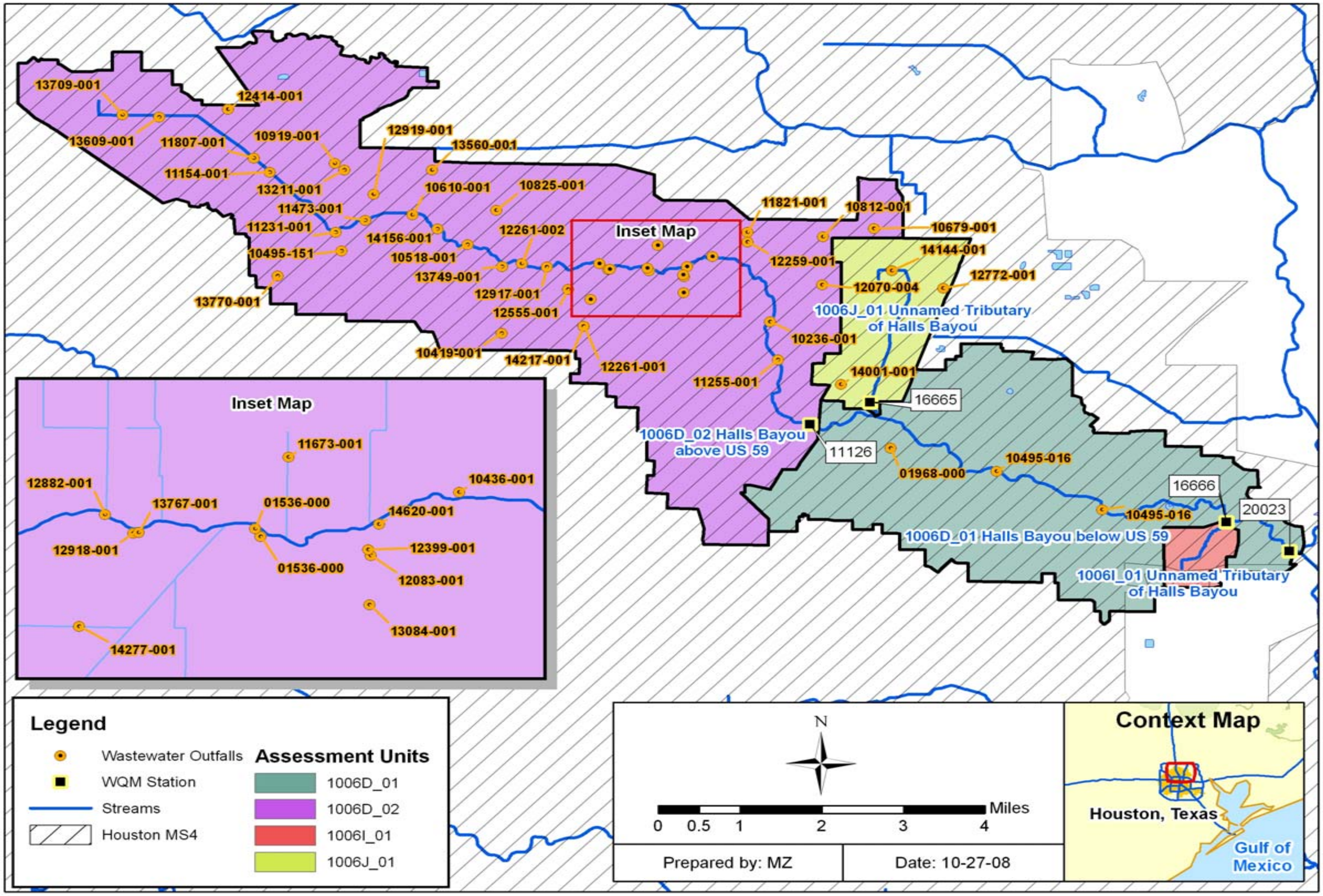
Segment	Stream Name	Assessment Unit	TPDES Number	NPDES NUMBER	Permittee Name	Facility Name	SIC	Facility Type	DTYPE	County	2008 Permitted Flow (MGD)	Average Monthly Flow (MGD)
		1006D_02	14921-001	TX0107158	JWR-HO LP	JWR-HO LP	4952	Sewerage Systems	D	HARRIS	0.032	0.008
		1006D_02	14932-001	TX0131849	Charleston Gardens Private Ud	Stripes LLC	4952	Sewerage Systems	D	HARRIS	0.005	NA
		1006D_02	13609-001	TX0115797	Aldine ISD	Aldine ISD Anne Louise Educ	8211	Elementary & Secondary Schools	D	HARRIS	0.042	0.016
		1006D_02	13709-001	TX0103071	White Palace LP	La Casita Homes	4952	Sewerage Systems	D	HARRIS	0.01	0.004
		1006D_02	13749-001	TX0122521	Sulyukmanov Nadija Balaban	Balaban Apartments WWTP	4952	Sewerage Systems	D	HARRIS	0.025	0.009
		1006D_02	13767-001	TX0095656	Fatima Family Village Inc	Fatima Family Village	4952	Sewerage Systems	D	HARRIS	0.012	0.008
		1006D_02	13770-001	TX0090735	William D. Smith	Sunset Mobile Home Park	NA	NA	D	HARRIS	0.06	NA
		1006D_02	14156-001	TX0122190	Lam Minh Thanh	West Mount Houston WWTP	4952	Sewerage Systems	D	HARRIS	0.003	0.001
		1006D_02	14217-001	TX0123579	Karbalai Laura Redow	Carby Road MHP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.02	0.010
		1006D_02	14277-001	TX0124265	Solhjou Ali Mohammad	Aldine Oaks Mobile Home Com	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.015	0.003
		1006D_02	14620-001	TX0127949	Solhjou Bahram	Barhram Solhjou WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.07	NA
		1006D_02	10919-001	TX0021237	Fallbrook Utility District	Fallbrook UD WWTP	4952	Sewerage Systems	W	HARRIS	1.3	1.001
		1006D_02	12919-001	TX0099171	Thomas, Tommy Joe	T J Thomas WWTP	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.018	0.007
		1006D_02	13211-001	TX0099104	Harris County MUD 321	Harris County MUD 321 WWTP	4952	Sewerage Systems	D	HARRIS	0.8	NA
1006J	Unnamed Tributary of Halls Bayou	1006J_01	12772-001	TX0093572	5510 Acorn LLC	5510 Acorn LLC	6515	Oper Of Res Mobile Home Sites	D	HARRIS	0.03	0.013
		1006J_01	14001-001	TX0117692	Hartman James William	Mcdonalds WWTP	5812	Eating Places	D	HARRIS	0.004	0.001
		1006J_01	14144-001	TX0120189	Galileo Mount Houston TX LP	Mount Houston WWTP	4952	Sewerage Systems	D	HARRIS	0.099	0.009

Source: TCE Water Quality Assessment Team. Personal Communication from Charles Marshall to Randy Palachek, May 28, 2008 (TCEQ 2008).
MGD = millions of gallons per day
NA = data not available
** flow from both outfalls for 10495-016 cannot exceed 7 MGD*
Type:
C = cooling water D = domestic <1 MGD S = storm water W = domestic >= 1 MGD or industrial process water, including water treatment plant discharge

Table 3-2 DMR Data for Permitted Wastewater Discharges (June 1998-June 2004)

NPDES Number	TPDES Number	Facility Name	Assessment Unit	Dates Monitored		# of Records	Number of MCMX Exceedances	Number of MCAV Exceedances	FC Daily Load (cfu)	
				Start	End				90 Percentile Monthly Average	Maximum Monthly Average
TX0063053	10495-016	City of Houston FWSD No. 23	1006D_01	06/30/2001	06/30/2004	8	8	8	6.40E+00	1.06E+11
TX0075663	10495-151	City of Houston	1006D_02	06/30/1998		1	0	0	NA	1.14E+10
TX0090492	12555-001	Westfield MHP Inc.	1006D_02	09/30/1998	03/31/2002	2	0	0	2.90E+07	1.51E+09

Source: TCEQ, September 2007
Notes: FC = Fecal Coliform
cfu = Colony Forming Unit
MCMX = Measurement: Concentration Maximum
MCAV = Measurement: Concentration Average



Source: The jurisdictional boundary of the Houston MS4 permit is derived from Urbanized Area Map Results for Texas *which can be found at the USEPA website* http://cfpub.epa.gov/npdes/stormwater/urbanmapresult.cfm?state=TX.

Figure 3-1 TPDES-Permitted Facilities in the Halls Bayou Watershed

3.1.2 Permitted Sources: NPDES No-Discharge Facilities and Sanitary Sewer Overflows

There are no No-Discharge Facilities located within the Study Area.

Sanitary sewer overflows (SSO) are permit violations that must be addressed by the responsible TPDES permittee. SSOs most often result from blockages in the sewer collection pipes caused by tree roots, grease and other debris. The TCEQ maintains a database of SSO data collected from wastewater operators in the Halls Bayou Watershed. In 2007, the City of Houston provided the project team a database summarizing SSO reported. These data are included in Appendix E and summarized in Table 3-3. Analysis of the most current data available, as can be seen from Table 3-3, indicates there were approximately 188 sanitary sewer overflows reported in the Halls Bayou Watershed between February 2001 and December 2003. The reported SSOs averaged 3,066 gallons per event. The locations and magnitudes of the all reported SSOs are displayed in Figure 3-2. The WWTF service area boundaries are also shown in Figure 3-2.

Table 3-3 Sanitary Sewer Overflow Summary

Facility Name	Receiving Water	Facility ID	Number of Occurrences	Date Range		Amount (Gallons)		
				From	To	Min	Max	Total Volume
City of Houston FWSD No. 23	1006D_01	10495-016	111	02/28/2001	12/04/2003	19	93,420	342,368
City of Houston FWSD No. 23	1006I_01	10495-016	10	04/13/2001	09/18/2003	48	30,792	66,458
Homestead[a]	1006D_01	10495-023	4	07/09/2001	09/26/2002	1	460	729
Northside Phase 1[b]	1006D_01	10495-090	16	06/12/2001	11/10/2003	44	6,484	23,875
Northside Phase 1[b]	1006D_02	10495-090	44	02/22/2001	10/29/2003	45	17,392	142,418
Northside Phase 1[b]	1006J_01	10495-090	1	09/24/2002	09/24/2002	280	280	280
City of Houston[c]	1006D_01	10495-148	2	07/27/2002	08/28/2003	103	145	248

[a] *The service area for Homestead (10495-023) covers part of 1006D_01*
[b] *The service area for Northside Phase 1 (10495-090) covers portions of 1006D_01, 1006D_02 and 1006J_01*
[c] *The service area for City of Houston (10495-148) covers portions of 1006D_01*

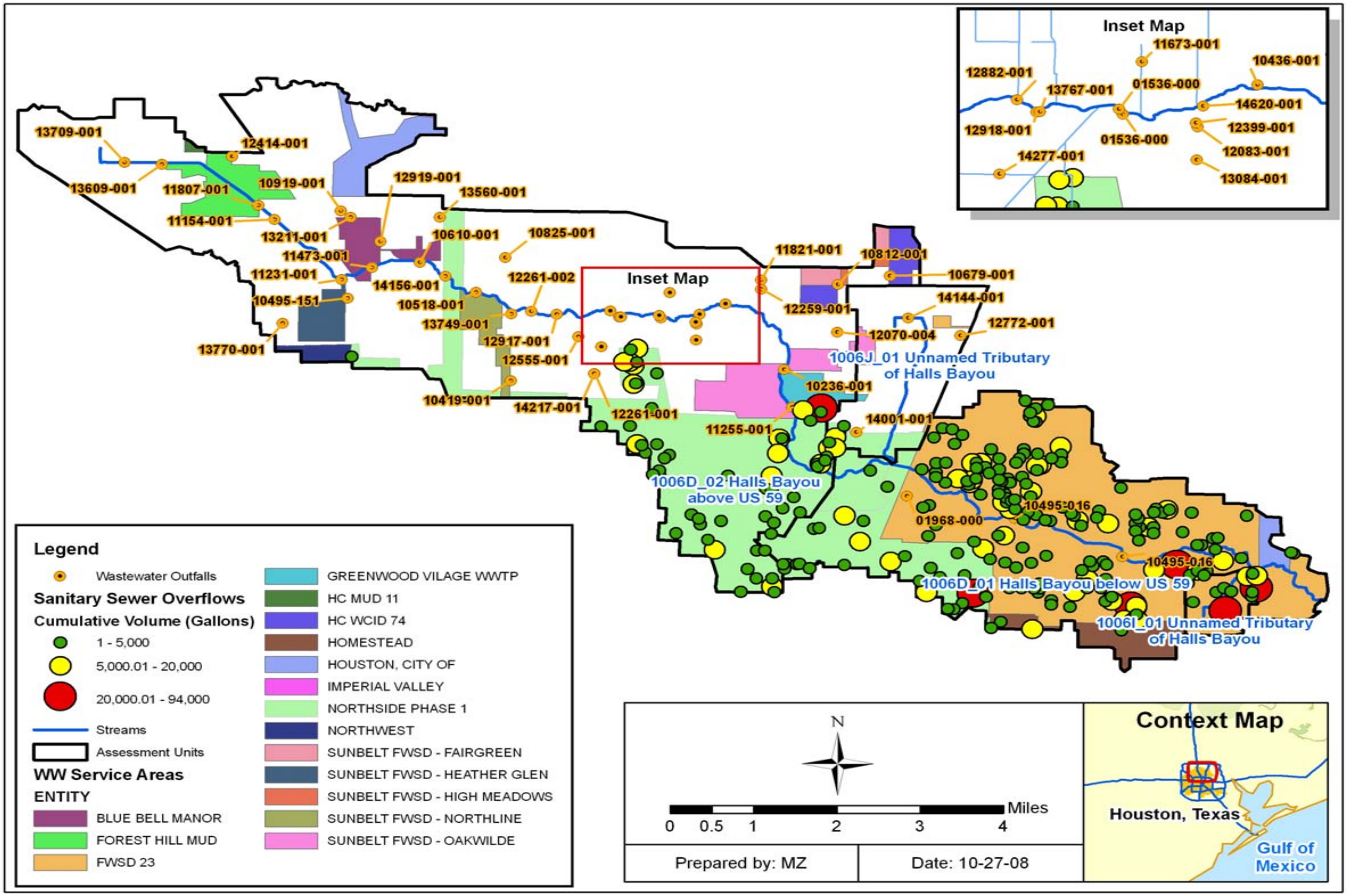


Figure 3-2 Sanitary Sewer Overflow Locations

3.1.3 Permitted Sources: TPDES Regulated Storm Water

In 1990, the USEPA developed rules establishing Phase I of the NPDES Storm Water Program, designed to prevent harmful nonpoint sources of pollutants from being washed by storm water 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 storm water management program as a means to control polluted discharges. Approved storm water 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 extends coverage of the NPDES Storm Water program to certain small MS4s. Small MS4s are defined as any MS4 that is not a medium or large MS4 covered by Phase I of the NPDES Storm Water Program. Phase II requires operators of regulated small MS4s to obtain NPDES permits and develop a storm water 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 Clean Water Act. Small MS4 storm water programs must address the following minimum control measures:

- 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 storm water runoff, a critical distinction must be made between storm water originating from an area under an NPDES/TPDES regulated discharge permit and storm water originating from areas not under an NPDES/TPDES regulated discharge permit. To characterize pollutant loads from storm water runoff, it is necessary to segregate storm water into two categories: 1) permitted storm water, which is storm water originating from an NPDES/TPDES-permitted Phase 1 or Phase 2 urbanized area; and 2) non-permitted storm water, which is storm water originating from any area outside an NPDES/TPDES-permitted Phase 1 or Phase 2 urbanized area. Considerable portions of each watershed in the Study Area are 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. Figure 3-1 displays the portion of the watershed that contributes bacteria loads to the receiving waters from areas of permitted and non-permitted storm water.

Under the City of Houston/Harris County permitted discharge permit, Harris County, HCFCD, City of Houston, and Texas Department of Transportation are designated as copermittees. Table 3-4 lists the percentage of area within each watershed covered under the Houston MS4 permit.

Table 3-4 Percentage of Permitted Storm Water in Each Watershed

Assessment Unit	Stream Name	TPDES Number	Total Area (acres)	Area under MS4 Permit (Acres)	Percent of Watershed under MS4 Jurisdiction
1006D_01	Halls Bayou below U.S. 59	WQ0004685000	8,182	8,007	98%
1006D_02	Halls Bayou above U.S. 59	WQ0004685000	18,090	18,090	100%
1006I_01	Unnamed Tributary of Halls Bayou	WQ0004685000	452	376	83%
1006J_01	Unnamed Tributary of Halls Bayou	WQ0004685000	1,839	1,839	100%

3.1.4 Dry Weather Discharges/Illicit Discharges

Bacteria loads from storm water can enter the streams from permitted outfalls and illicit discharges under both dry and wet weather conditions. Dry-weather and illicit discharges are regulated under WWTF permits, and where applicable, under the provisions of an MS4. The term "illicit discharge" is defined in EPA's Phase II storm water regulations as "any discharge to a municipal separate storm sewer that is not composed entirely of storm water, except discharges pursuant to an NPDES permit and discharges resulting from fire-fighting activities" (NEIWPCC 2003).

Illicit discharges can be categorized as either direct or indirect contributions. Examples of illicit discharges identified in the *Illicit Discharge Detection and Elimination Manual: A Handbook for Municipalities* (NEIWPCC 2003) include

Direct illicit discharges:

- sanitary wastewater piping that is directly connected from a home to the storm sewer;
- materials (e.g., used motor oil) that have been dumped illegally into a storm drain catch basin;
- a shop floor drain that is connected to the storm sewer; and
- a cross-connection between the municipal sewer and storm sewer systems.

Indirect illicit discharges:

- an old and damaged sanitary sewer line that is leaking fluids into a cracked storm sewer line; and
- a failing septic system that is leaking into a cracked storm sewer line or causing surface discharge into the storm sewer.

Various investigations have been conducted in localized areas of Houston. Data from neighboring watersheds (Buffalo and Whiteoak Bayous) demonstrate that illicit discharges are a source of significant indicator bacteria load**.** While the dry weather flows from the storm sewer network in Buffalo and Whiteoak Bayous were small relative to the other dry weather flows, the *E. coli* concentrations measured were at times very high (similar to the levels found in raw sewage). An outfall inventory survey has not been completed for Brays Bayou and dry weather discharges from the storm sewer network have not been sampled therefore, there is insufficient data to adequately quantify the magnitude of indicator bacteria loads from illicit discharges in the Brays Bayou watershed.

3.1.5 Wet Weather Facilities

Wet weather facilities (WWF) are surge tankage facilities in the sanitary sewer system that act to moderate wastewater flow peaks similarly to a stormwater detention basin. If the surge tankage capacity is not exceeded, the tank volume is returned to the sewer after the flow subsides. If the capacity is exceeded, the excess is discharged after settling and disinfection. The City of Houston-Bretshire Plant is the only permitted WWF discharging to Halls Bayou. It is located in the vicinity of the FWSD No. 23 WWTP (10495-016 in Figure 3-2) and discharges to assessment unit 1006D_01.

Permit requirements for the WWFs establish that discharges be monitored and that receiving water body be monitored both upstream and downstream of the discharge. Relevant monitoring data for the period September 1998-June 2004 for the Bretshire WWF, provided by the City of Houston, are presented in Table 3-5. The ranges of measured fecal coliform data at the three monitoring locations (discharge, upstream, and downstream) are shown in Figure 3-3. It can be seen that the fecal coliform levels in the Bretshire WWF are usually very high and the overall geometric mean is about five times those for the stream sampling. However, because the WWF discharge is much lower than the flows measured at the bayou (average flow of 5 cfs compared to approximately 1900 cfs in the bayou), the expected load of fecal coliform from the WWF is not expected to have a substantial impact on the water quality of the bayou. This is confirmed by data in Figure 3-3, which shows that the downstream concentrations are within the same order of magnitude as the upstream concentrations.

Table 3-5 Bretshire WWF Monitoring Data

Date	Flow (cfs)			Fecal Coliform (cfu/100mL)		
	Discharge	Upstream	Downstream	Discharge	Upstream	Downstream
9/11/1998	11.84	4,350	4,410	24,000	32,000	38,000
10/18/1998	7.26	1,390	1,390	470,000	44,000	49,000
11/12/1998	3.09	1,850	1,850	990,000	36,000	20,000
11/14/1998	6.54	1,650	1,650	250,000	28,000	25,000
12/11/1998	9.19	1,900	1,970	200	49,000	39,000
5/12/1999	7.26	2,060	2,020	2,300,000	39,000	34,000
7/9/2003	0.64	135	140	930,000	51,000	44,000
11/17/2003	0.02	3,100	3,200	1,900,000	49,000	41,000
5/1/2004	3.05	1,600	1,600	760	55,000	41,000
6/24/2004	4.24	1,880	1,800	690,000	49,000	31,000
6/25/2004	1.4	950	1,005	8,000,000	41,000	38,000
Geomean (count/dL)				186,545	42,165	35,345
Average (cfs)	5.0	1,896.8	1,912.3			

[a] *A concentration equal to 1 cfu/100mL was assumed for geometric mean calculations.*

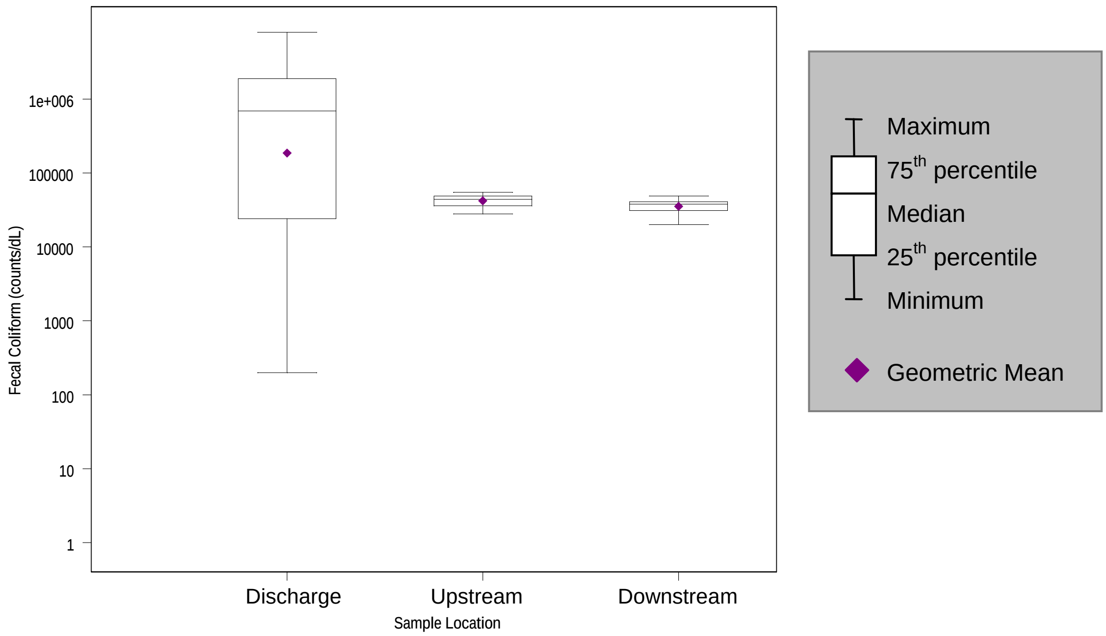


Figure 3-3 Fecal Coliform Monitoring Data from Bretshire WWF

3.1.6 Concentrated Animal Feeding Operations

There are no CAFOs located within the Study Area.

3.2 Non-permitted Sources: Storm Water, On-site Sewage Facilities, and Direct Deposition

Non-permitted sources (nonpoint sources) include those sources that cannot be identified as entering the waterbody at a specific location. Bacteria originate from rural, suburban, and urban areas. The following section describes possible major non-permitted sources contributing indicator 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 storm water runoff (USEPA 1983). Non-permitted storm water can be a significant source of fecal bacteria.

3.2.1 Wildlife and Unmanaged Animal Contributions

Fecal coliform and *E. coli* 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 is 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. Fecal bacteria from wildlife are also deposited onto land surfaces, where it may be washed into nearby streams by rainfall runoff. Typical of coastal watersheds, there is a significant population of avian species that frequent the watershed and the riparian corridors, in particular. However, currently there are 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.

3.2.2 Non-Permitted Agricultural Activities and Domesticated Animals

There are a number of non-permitted agricultural activities that can also be sources of fecal bacteria loading. Given the fact that the Greens Bayou Watershed is highly urbanized, livestock and other domesticated animals are not found in these watersheds and therefore are not considered as a contributor of bacteria loads.

3.2.3 Failing On-site Sewage Facilities

On-site sewage facilities 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. Fecal coliform-contaminated groundwater can also be discharged to creeks through springs and seeps.

Over time, most OSSFs operating at full capacity will fail. 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, which is part of Region 4, 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 3-6 lists the OSSF totals based on the 1990 U.S. census and the number of OSSF permits obtained by authorized county or city agents between 1992 -2007. Permits are obtained to install or replace systems. However, some permits are obtained when an older failing system needs repair (Houston-Galveston Area Council [H-GAC] 2005). It is assumed that more OSSFs were installed in Harris County prior to 1992 than listed in Table 3-6.

Table 3-6 Numbers of OSSF Permits Issued by Authorized County or City Agent

Year	Harris
1990 Census Totals	44,120
1992	243
1993	651
1994	881
1995	1,035
1996	1,327
1997	1,393
1998	1,301
1999	1,606
2000	1,422
2001	1,388
2002	1,397
2003	1,424
2004	1,174
2005	1,080
2006	1,039
2007*	498
Total	**61,979**

Note: Data obtained from TCEQ On-Site Activity Reporting System
** only data up to 8/8/2007 were available*

To estimate the potential magnitude of fecal bacteria loading from OSSFs, the number of OSSFs was estimated for each watershed. The estimate of OSSFs was derived by using data from the 1990 U.S. census (U.S. Census Bureau 2000) and a GIS shapefile obtained from H-GAC showing all areas where wastewater service currently exists. Figure 3-4 displays unsewered areas that did not fall under the wastewater service areas. OSSFs were calculated using spatial GIS queries for areas not covered by wastewater service areas. OSSFs were assigned proportionally based on the percentage of the area falling outside a wastewater service area within each watershed. Finally, the OSSFs for each unsewered area were then totaled by TMDL watershed. This approach gives an estimate of OSSFs in the watershed. Table 3-7 shows the estimated number of OSSFs calculated using this GIS method.

Harris County provided a GIS shapefile showing the locations of potential OSSF violations from 2006-2007. Data are shown for areas not covered by wastewater service in Figure 3-4.

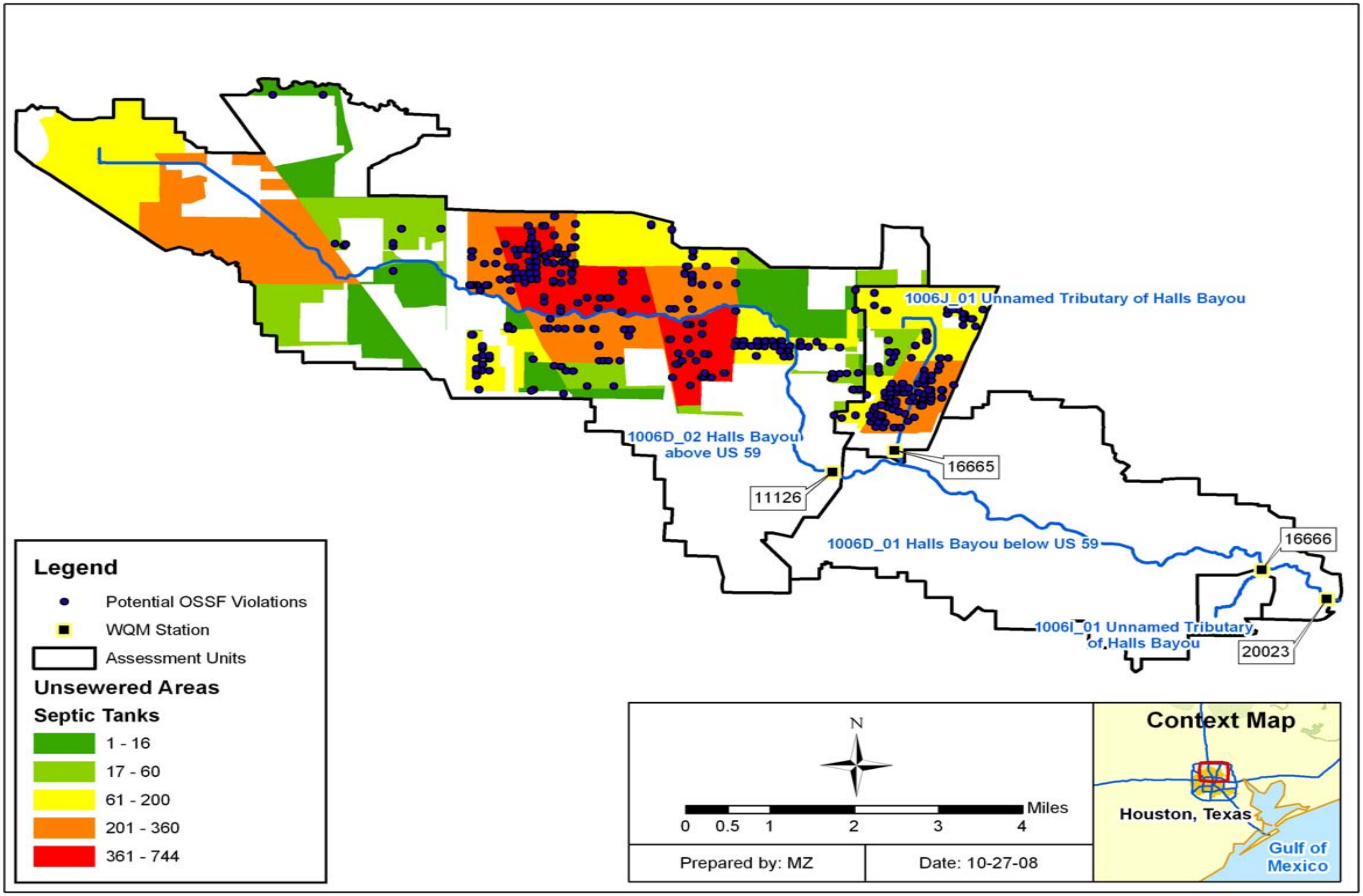


Figure 3-4 Unsewered Areas and Subdivisions with OSSF

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):

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

The average of number of people per household was calculated to be 2.79 for Harris County (U.S. Census Bureau 2000). 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 septic tank effluent was estimated to be 10^6 per dL 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 potential violation septic systems within the watersheds was summarized below in Table 3-7. Based on these data, the estimated fecal coliform loading from OSSFs in the Study Area was found to be negligible.

Table 3-7 Estimated Number of OSSFs per Watershed and Fecal Coliform Load

Assessment Unit	Stream Name	OSSF Estimate using 1990 Census Method	# of Failing Septic Tanks[a]	Potential Violation Database[b]	Estimated Loads from Septic Tanks ($x10^9$ counts/day)[c]
1006D_01	Halls Bayou below U.S. 59	0	0	0	0
1006D_02	Halls Bayou above U.S. 59	4,042	485	436	3,586
1006I_01	Unnamed Tributary of Halls Bayou	0	0	0	0
1006J_01	Unnamed Tributary of Halls Bayou	1,157	139	175	1,026

[a] A 12% failure rate was multiplied by the number of OSSFs estimated derived from the 1990 census.
[b] The Potential Violation Database was obtained from Harris County (2006-2007).
[c] Load estimate was based on literature values for fecal coliform concentrations since no E. coli concentration values were available. This calculation was based on the number of failing septic tanks.

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 2004). Using the U.S. census data at the block level (U.S. Census Bureau 2000), dog and cat populations can be estimated for each watershed. Table 3-8 summarizes the estimated number of dogs and cats for the watersheds of the Study Area.

Table 3-8 Estimated Numbers of Pets

Assessment Unit	Stream Name	Dogs	Cats
1006D_01	Halls Bayou below U.S. 59	10,956	12,467
1006D_02	Halls Bayou above U.S. 59	15,400	17,524
1006I_01	Unnamed Tributary of Halls Bayou	1,220	1,389
1006J_01	Unnamed Tributary of Halls Bayou	3,433	3,907

Table 3-9 provides an estimate of the fecal coliform load from pets. These estimates are based on estimated fecal coliform production rates of 5.4×10^8 per day for cats and 3.3×10^9 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 3-9 Estimated Fecal Coliform Daily Production by Pets (x 10^9)

Assessment Unit	Stream Name	Dogs	Cats	Total
1006D_01	Halls Bayou below U.S. 59	36,154	6,732	42,886
1006D_02	Halls Bayou above U.S. 59	50,819	9,463	60,282
1006I_01	Unnamed Tributary of Halls Bayou	4,027	750	4,777
1006J_01	Unnamed Tributary of Halls Bayou	11,329	2,110	13,438

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 is shown in the general literature 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.

SECTION 4
TECHNICAL APPROACH AND METHODS

The objective of a TMDL is to estimate allowable pollutant loads and to allocate these loads to the known pollutant sources in the watershed so appropriate control measures can be implemented and the standard for contact recreation achieved. A TMDL is expressed as the sum of three elements as described in the following mathematical equation:

TMDL = Σ WLA + Σ 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 non-permitted (nonpoint) sources, including natural background sources. The MOS is intended to 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* bacteria, TMDLs are expressed as numbers per day and represent the maximum one day load the stream can assimilate while still attaining the standard for contact recreation. For the Halls 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 using the load duration curve (LDC) method as 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 rapid development of TMDLs, and as a TMDL development tool, are 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:

- preparing flow duration curves (FDC) for gaged and ungaged WQM stations;
- estimating existing bacteria loading in the receiving water using ambient water quality data;
- using LDCs to identify the critical condition that will dictate loading reductions necessary to attain the contact recreation standard; and
- 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 adequate water quality across 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 effluents 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, equal to the line, 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. FDCs utilize the historical 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. In developing the FDC presented in this report, a more complex approach was used that also considers watershed differences in rainfall, land use, WWTF discharges, and the hydrologic properties of soil that govern runoff and retention. More than one upstream flow gage may also be considered. 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. Because the only USGS gage on the Study Area does not have a complete record for the 1996-2006 period, it was necessary to estimate flows using a neighboring gage. Therefore, USGS gage 08076000 (Greens Bayou near Houston, Texas) was chosen to conduct flow projections to establish estimated flows for each of these freshwater segments. The period of record for flow data used from this station was 1996 through 2006.

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 for the Halls Bayou Watershed is outlined 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

The low flow category was derived by calculating the percentage of bayou flows contributed by WWTFs using the long-term average reported flows. Since the flows from WWTFs represent less than the 15^{th} percentile of the stream flows, "low flows" were assumed to be exceeded between 80 and 100 percent of the time. Some instantaneous flow measurements were available from the intensive surveys collected for this project. These were not combined with the daily average flows or used in calculating flow percentiles, but were matched to bacteria grab measurements collected at the same site and time. When available, these instantaneous flow measurements were used in lieu of the daily average flow to calculate instantaneous bacteria loads.

Figures 4-1 through 4-5 present the FDCs developed for the downstream WQM station used for calculating the TMDLs of each 303(d) listed freshwater stream using the flow projection method outlined above and further described in Appendix F. The flow exceedance percentiles for each WQM station described below and presented in the figures are provided in Appendix G.

Figure 4-1 represents the FDC for Halls Bayou below U.S. 59, assessment unit 1006D_01 at WQM station 20023. Because WWTFs discharge to this segment, average monthly WWTF flows obtained from DMRs were added to the projected flow.

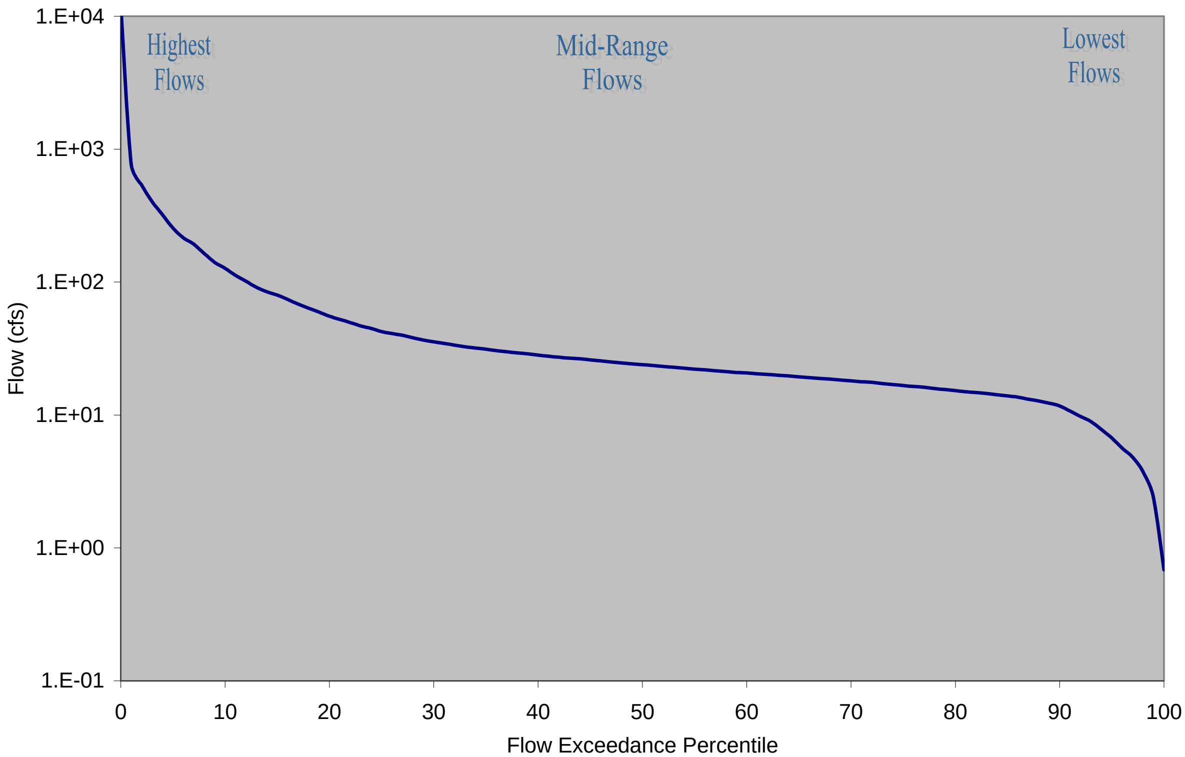


Figure 4-1 Flow Duration Curve for Halls Bayou below U.S. 59 (1006D_01)

Figure 4-2 represents the FDC for Halls Bayou above U.S. 59, assessment unit 1006D_02 at WQM station 11126. Daily flow data were available at USGS gage station 8076500 (Halls Bayou at Houston, Texas) for the time period 10/1/2000 to present. Therefore, the remainders of daily flows for the period of 1996 through 2006 used to develop the FDC were estimated from USGS gage station 08076000 (Greens Bayou near Houston, Texas). Because WWTF discharges occur in this water quality segment, average monthly WWTF flows obtained from DMRs were added to the projected flow. No DMR data were available for TX0090735, TX0127949 and TX0099104. Therefore, half of the permitted flow for these facilities was added to the projected flow.

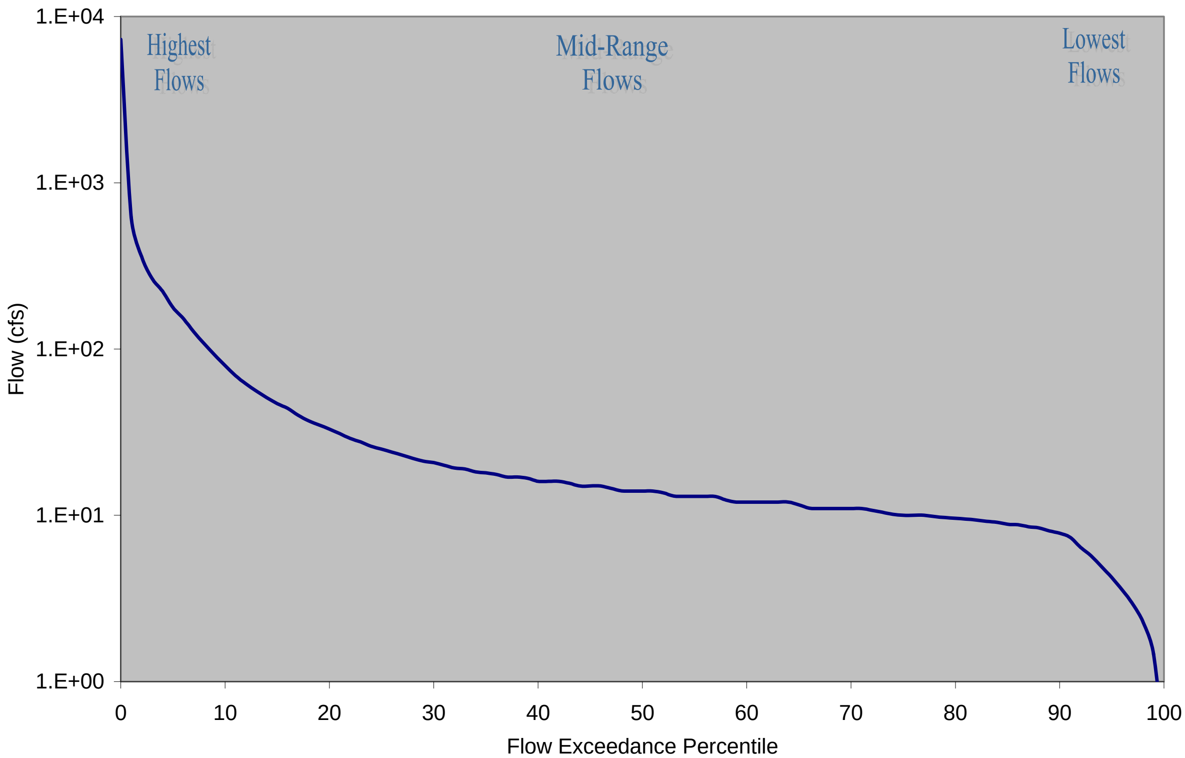


Figure 4-2 Flow Duration Curve for Halls Bayou above U.S. 59 (1006D_02)

Figure 4-3 represents the FDC for Unnamed Tributary of Halls Bayou, assessment unit 1006I_01 at WQM station 16666. Since no WWTFs discharge to this segment, the flows projected using the methods described in Appendix F were not modified.

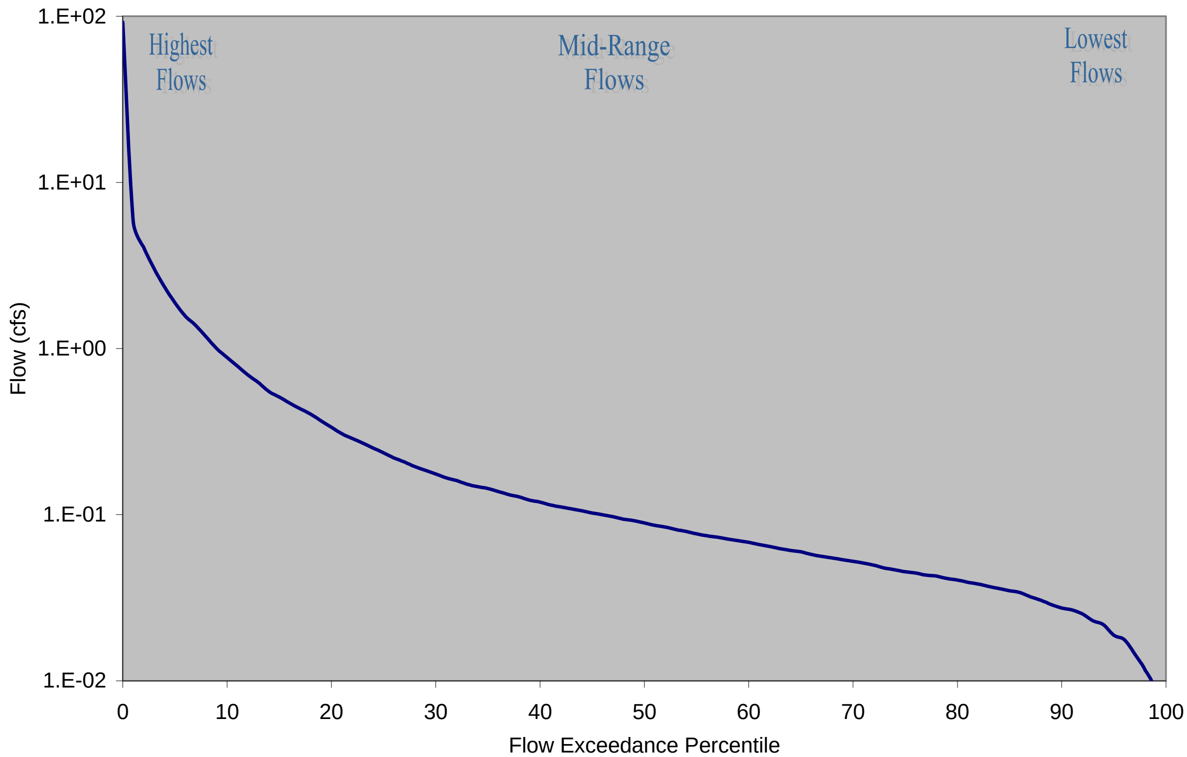


Figure 4-3 Flow Duration Curve for Unnamed Tributary of Halls Bayou (1006I_01)

Figure 4-4 represents the FDC for Unnamed Tributary of Halls Bayou, assessment Unit 1006J_01 at WQM station 16665. Because WWTF discharges occur in this segment, average monthly WWTF flows obtained from DMRs were added to the projected flow.

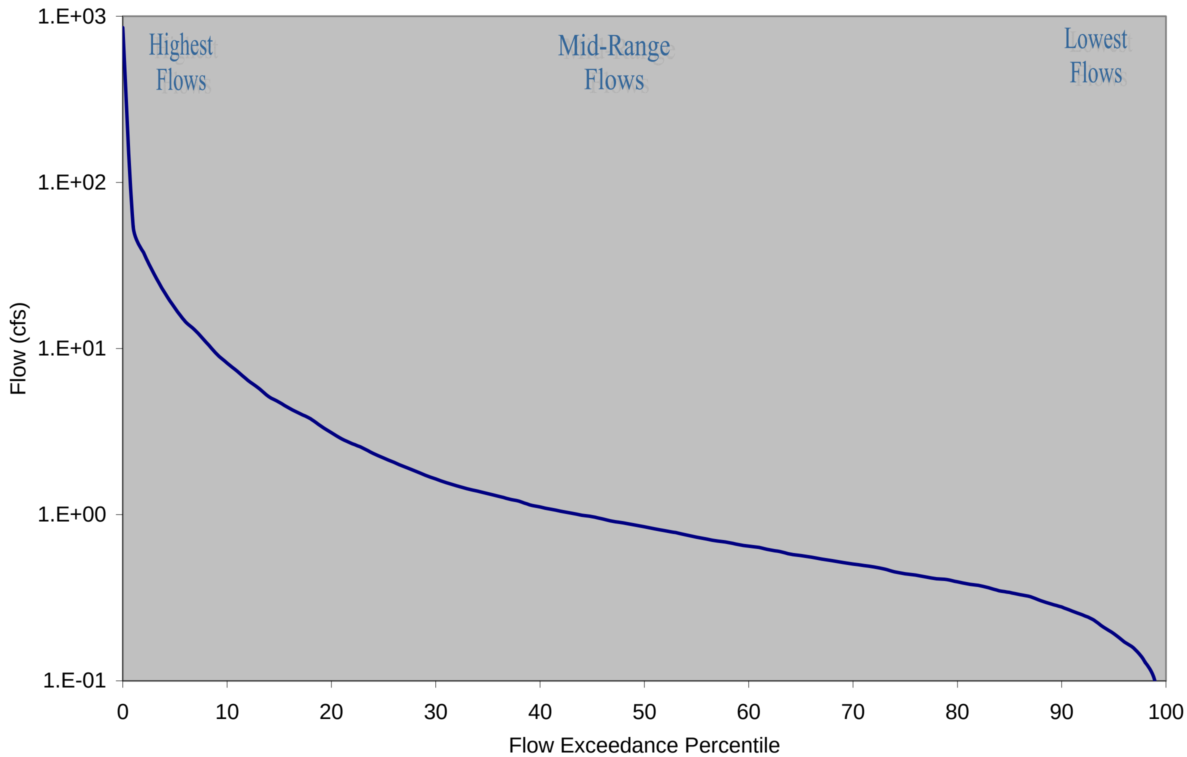


Figure 4-4 Flow Duration Curve for Unnamed Tributary of Halls Bayou (1006J_01)

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. In Texas, WWTFs that discharge treated sanitary wastewater must meet the criteria for indicator bacteria at the point of discharge. However, for TMDL analysis it is necessary to understand the relative contribution of WWTFs to the overall pollutant load and its general compliance with required effluent limits. The monthly bacteria load for continuous point source dischargers is estimated by multiplying the monthly average flow rates by the monthly geometric mean bacteria concentration, with a volumetric conversion factor. Where available, fecal coliform data for this calculation were extracted from each point source's discharge monitoring reports from 1996 through 2006. The current pollutant loading from each permitted point source discharge is calculated using the equation below:

*Point Source Loading = monthly average flow rates (mgd) * geometric mean of corresponding fecal coliform concentration * unit conversion factor*

Where:

unit conversion factor = 37,854,120 dL/million gallons (mg)

It is difficult to estimate current nonpoint loading due to lack of specific water quality and flow information that would assist in estimating the relative proportion of non-specific sources within the watershed. Therefore, existing instream loads were used as a conservative surrogate for nonpoint loading. Existing instream loads were calculated using measured bacteria concentrations from WQM stations multiplied by the flow rate (estimated or instantaneous) under various flow conditions.

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

The final step in the TMDL calculation process involves a group of additional computations derived from the preparation of LDCs. These computations are necessary to derive a percent reduction goal (one method of presenting how much bacteria loading must be reduced to meet the water quality criterion in an impaired watershed).

Step 1: Generate Bacteria LDCs. LDCs are similar in appearance to flow duration curves; however, the y-axis is expressed in terms of a bacteria load in counts/day. The curve represents the instantaneous water quality criterion for *E. coli* (394 MPN/100mL), expressed in terms of a load through multiplication by the continuum of flows historically observed at this site. Using the single sample water quality criterion to generate the LDC is necessary to display the allowable pollutant load in relation to the existing loads, which are represented by existing ambient water quality samples. The basic steps to generating an LDC involve:

- obtaining daily flow data for the WQM station of interest from the USGS;
- sorting the flow data and calculating flow exceedance percentiles for the time period and season of interest;
- obtaining the water quality data;
- matching the water quality observations with the flow data from the same date;
- displaying a curve on a plot that represents the allowable load multiply the actual or estimated flow by the SWQS for each respective indicator;
- multiplying the flow by the water quality parameter concentration to calculate daily loads; then
- plotting the flow exceedance percentiles and daily load observations in a load duration plot.

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 = 394 MPN/100mL (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 (MPN/100mL) by the instantaneous flow (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 non-permitted 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.

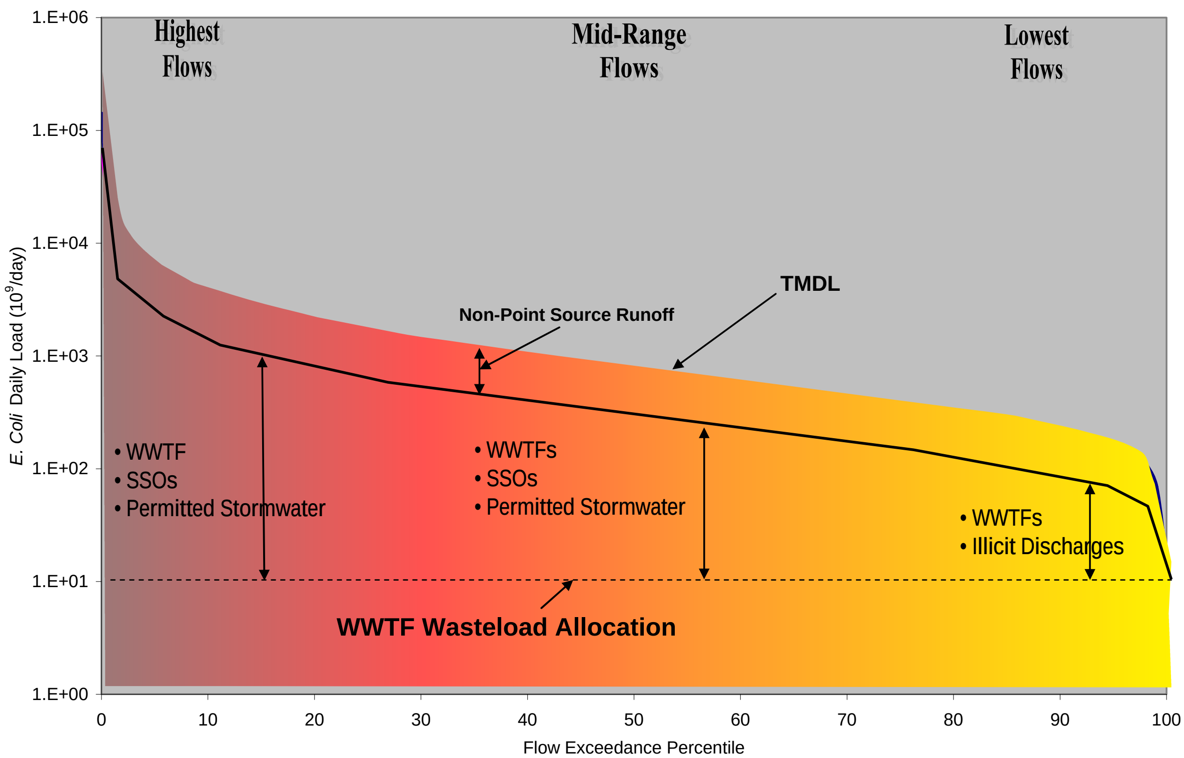


Figure 4-5 LDC Schematic Diagram – Interpreting Sources and Loads

To determine if a bacteria sample was influenced by runoff, rainfall data from the rain gage closest to a WQM station were evaluated. The potential maximum retention after runoff begins (S) was calculated to determine how much rainfall would be needed to produce runoff for each watershed. S is calculated using the formula below:

$$S = \frac{1000}{CN} - 10$$

Where: S = potential maximum retention after runoff begins (inches)

CN =average curve number for the watershed

Three-day rainfall totals were then calculated for each rain gage. These data were matched to the date the bacteria sample was collected. A bacteria sample was then considered a wet weather sample if the three-day rainfall total was greater than or equal to *S*. These bacteria samples were then plotted in the LDCs using a different symbol from those samples that were not considered wet weather influenced.

Step 2: Develop LDCs with MOS. The MOS may be defined explicitly or implicitly. A 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. In an implicit MOS approach, conservative assumptions used in developing the TMDL are relied upon to provide an MOS to assure that the water quality target for contact recreation is attained.

For the TMDLs for freshwater streams in this report, an explicit MOS of 5 percent of the TMDL value (5% of the instantaneous water quality criterion) has been selected to slightly reduce assimilative capacity in the watershed. 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 (continuous) or storm water permitted discharge. Storm water point sources are typically associated with urban and industrialized areas, and recent USEPA guidance includes NPDES-permitted storm water 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 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 average 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 WWTFs 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/2 * flow * unit conversion factor (#/day)*

Where: criterion = 126 MPN/100mL (E. coli)

flow (mgd) = permitted flow

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

WLA for NPDES/TPDES Storm Water. Given the lack of data and the complexity of quantifying bacteria concentrations or loads associated with wet weather events, calculating the WLA for permitted storm water (MS4) discharges must be derived in a manner similar to that used for all other non-permitted nonpoint sources. In other words it must be derived from the overall LA or the area under the TMDL curve and above the WLA established for WWTFs. Rather than one discrete value, which is practical for WWTF discharges, the WLA calculations for permitted storm water discharges must be expressed as different maximum loads allowable under different flow conditions. Therefore, the percentage of a watershed that is under MS4 jurisdiction is used to estimate the load that should be allocated as the permitted storm water load. For example, the coverage area of the City of Houston/Harris County permitted MS4 discharge in assessment unit 1006I_01 is estimated to be 376 acres or 83 percent of the watershed. Therefore, 83 percent of the LA calculated at any flow condition will be designated as the WLA_{MS4} for the City of Houston as part of the TMDL for segment 1006I_01.WLA.

Step 4: Calculate LA. LAs for non-permitted 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 storm water. The LA is represented by the area under the LDC but above the WLA. The LA at any particular flow exceedance is calculated as shown in the equation below.

$$LA = TMDL – MOS - \Sigma WLA_{WWTF} – \Sigma WLA_{STORM\ WATER}$$

Where:

LA = allowable load from non-permitted sources
TMDL= total allowable load
ΣWLA_{WWTF} = sum of all WWTF loads
$\Sigma WLA_{STORM\ WATER}$ = sum of all STORM WATER loads
MOS = margin of safety

Step 5: Estimate WLA Load Reduction. The WLA load reduction for TPDES-permitted WWTFs was not calculated since it was assumed that continuous dischargers are adequately regulated under existing permits and, therefore, no WLA reduction would be required. However, for permitted storm water 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. After existing loading estimates are computed for the indicator bacteria, nonpoint load reduction estimates for each sampling location are calculated by using the difference between estimated existing loading and the allowable load expressed by the LDC (TMDL-MOS). Existing loads were determined by using the median flow of each of the three flow regimes multiplied by the geometric mean concentration of the historical bacteria data within a given regime. For example, for the 0-20th percentile flow range, the flow corresponding to the 10th percentile was used. The geometric mean of the indicator bacteria samples within the 0-20th flow percentile range was then multiplied by the flow corresponding to the 10th exceedance percentile to determine the existing load. Overall, percent reduction goals were also calculated for the most-downstream station of each segment. The highest reduction determined for each segment is then applied as the percent reduction goal. In this case, all indicator bacteria data from flow exceedance percentiles of 0 through 100 were used to calculate the geometric mean and the percent reduction goal was derived using the following formula:

Percent Reduction Goal = (Geometric Mean of Indicator Bacteria Data – Water Quality Target) 100*

Figures 4-6 through 4-9 present the LDCs developed for the downstream WQM station used for calculating the TMDLs of each 303(d) listed waterbody.

Figure 4-6 represents the LDC for Halls Bayou below U.S. 59 and is based on *E. coli* bacteria measurements at sampling location 20023 (Halls Bayou near north end of Banting Street). The LDC indicates that *E. coli* levels exceed both the instantaneous and geometric mean water quality criteria under high and mid-range flow conditions. Wet weather influenced *E. coli* observations are found under high and mid range flow conditions. The last part of the curve (above the 97th percentile), where loads at WQ target are lower than the WWTF wasteload, is assumed to be equal to the WLA_{WWTF}. This explains the difference of shape between the LDC and FDC at very low flows.

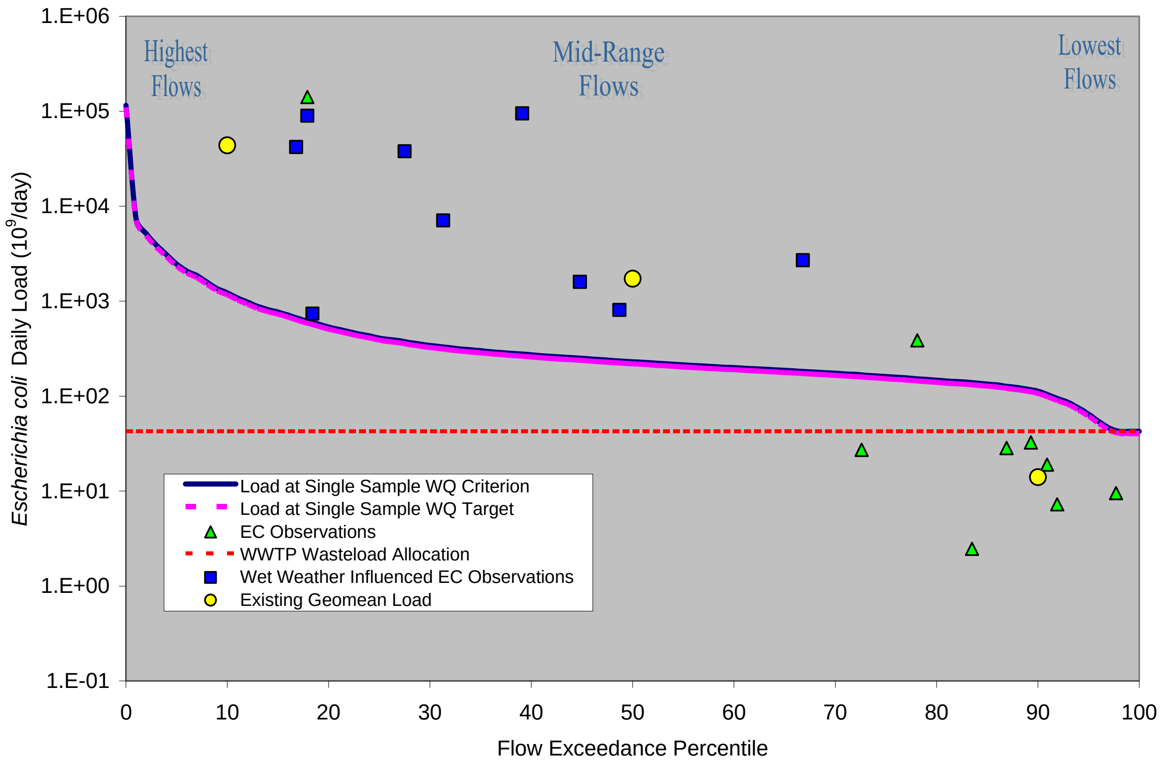


Figure 4-6 Load Duration Curve for Halls Bayou below U.S. 59 (1006D_01)

Figure 4-7 represents the LDC for Halls Bayou above U.S. 59 and is based on *E. coli* bacteria measurements at sampling location 11126 (Halls Bayou at Jensen Drive). The LDC indicates that *E. coli* levels exceed both the instantaneous and geometric mean water quality criteria under all flow conditions. Wet weather influenced *E. coli* observations are found under all flow conditions. Wet weather influenced samples found during low flow conditions can be caused by an isolated rainfall event during dry conditions. The last part of the curve (above the 98th percentile), where the loads at WQ target are lower than the WWTF wasteload allocation, is assumed to be equal to the WLA-WWTF. This explains the difference of shape between the LDC and FDC at very low flows.

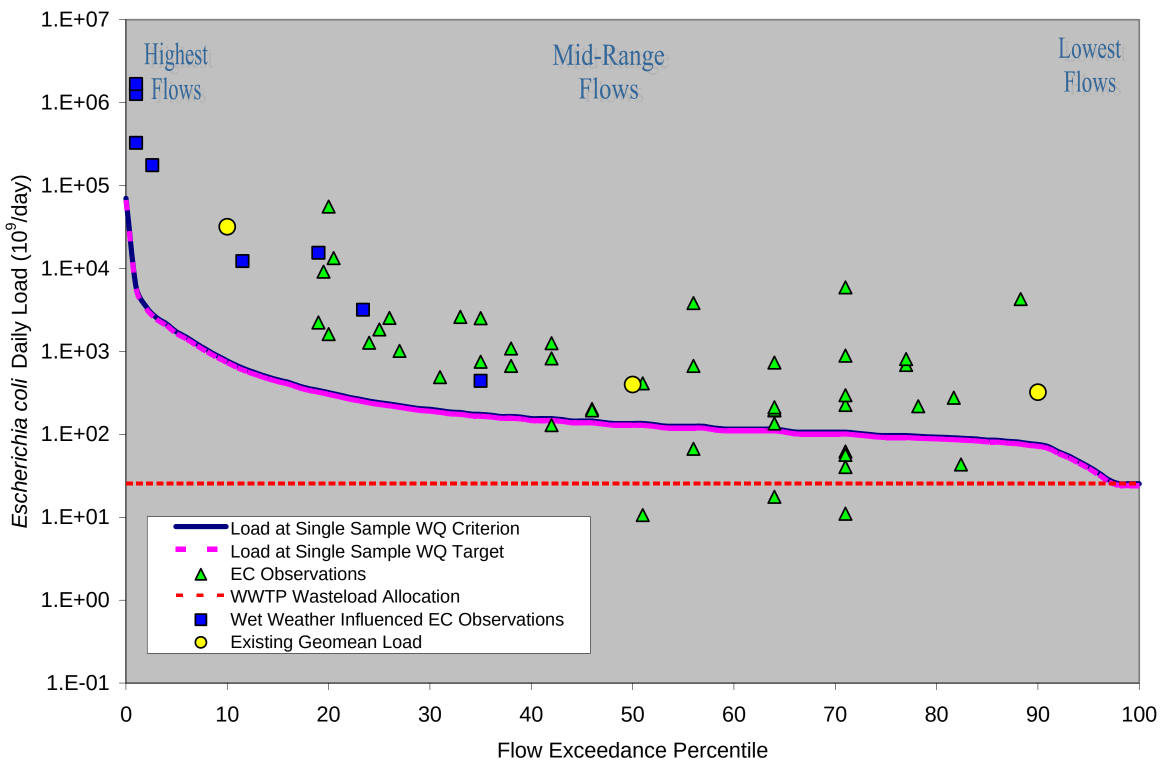


Figure 4-7 Load Duration Curve for Halls Bayou above U.S. 59 (1006D_02)

Figure 4-8 represents the LDC for Unnamed Tributary of Halls Bayou and is based on *E. coli* bacteria measurements at sampling location 16666 (Unnamed Tributary of Halls Bayou at Talton Street). The LDC indicates that *E. coli* levels exceed the instantaneous and geometric mean water quality criteria under all flow conditions. Wet weather influenced *E. coli* observations are found under all flow conditions. Wet weather influenced samples found during low flow conditions can be caused by an isolated rainfall event during dry conditions.

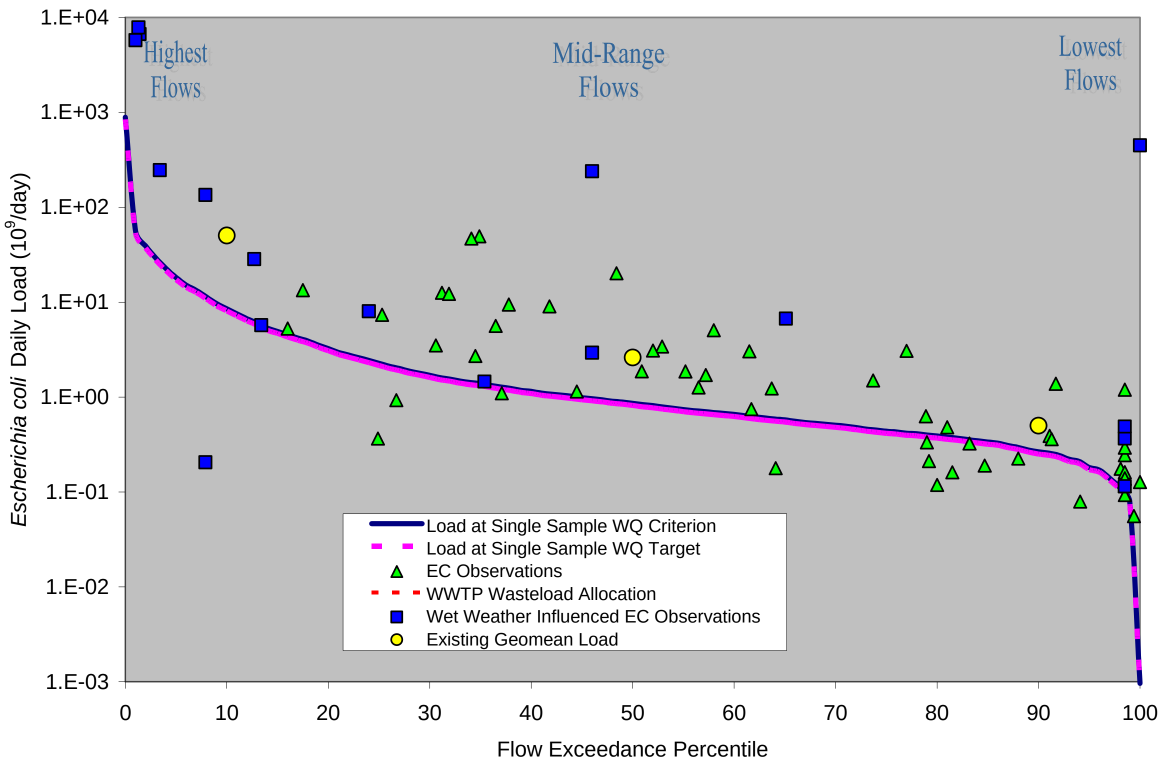


Figure 4-8 Load Duration Curve for Unnamed Tributary of Halls Bayou (1006I_01)

Figure 4-9 represents the LDC for Unnamed Tributary of Halls Bayou and is based on *E. coli* bacteria measurements at sampling location 16665 (Unnamed Tributary of Halls Bayou downstream of Langley Road). The LDC indicates that *E. coli* levels exceed both the instantaneous and geometric mean water quality criteria under all flow conditions. Wet weather influenced *E. coli* observations are found under high and mid range flow conditions.

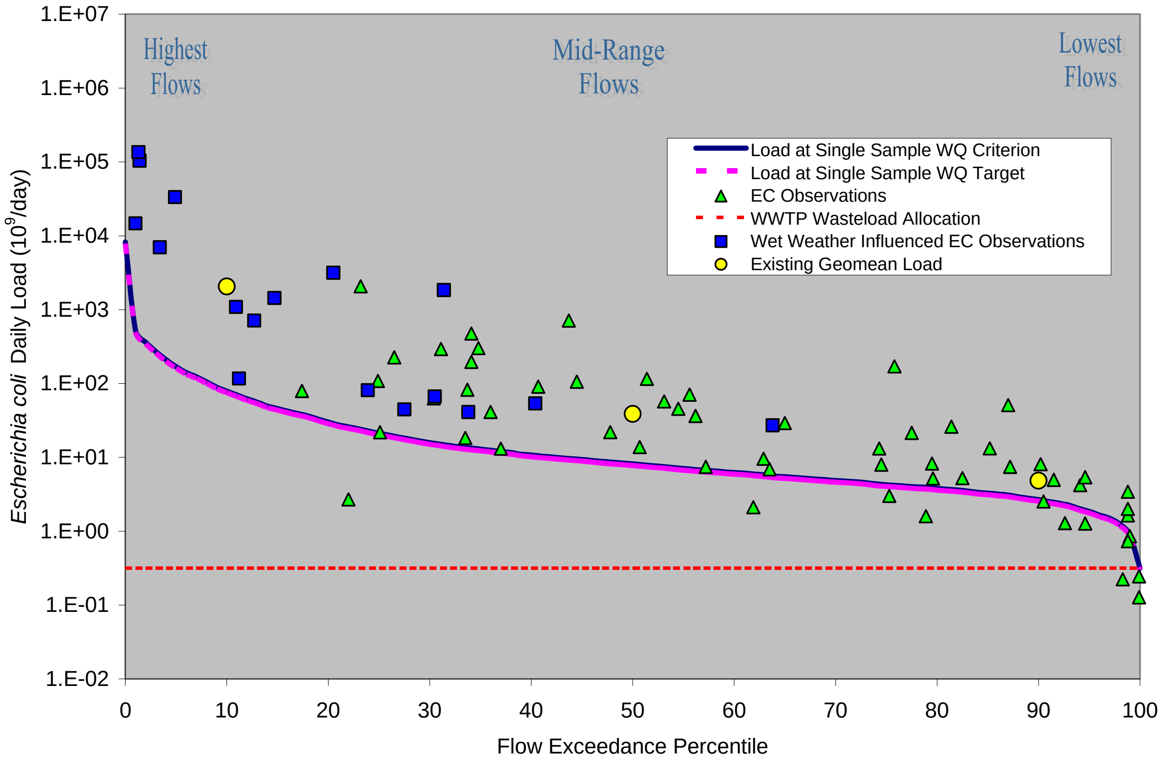


Figure 4-9 Load Duration Curve for Unnamed Tributary of Halls Bayou (1006J_01)

4.5 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 and the magnitude of water quality criteria exceedance. TMDLs are derived for indicator bacteria in 303(d) listed water bodies at specific WQM stations based on LDCs for freshwater streams.

To calculate the bacteria load at the criterion for freshwater segments, the flow rate at each flow exceedance percentile is multiplied by a unit conversion factor (*24,465,755 dL/ft3 * seconds/day*) and the criterion specific to each indicator bacteria. This calculation produces the maximum bacteria load in the stream without exceeding the instantaneous standard over the range of flow conditions. In the case of *E. coli* for freshwater streams, the allowable geometric mean concentrations defined in the SWQS are the TMDL. *E. coli* is plotted versus flow exceedance percentiles as a LDC. The x-axis indicates the flow exceedance percentile, while the y-axis is expressed in terms of a bacteria load.

To estimate existing loading, bacteria observations from 2000 to 2006 are paired with the flows measured or estimated in that segment on the same date. Pollutant loads are then calculated by multiplying the measured bacteria concentration by the flow rate and a unit conversion factor of *24,465,755 dL/ft3 * seconds/day*. The associated flow exceedance percentile is then matched with the measured flow from the tables provided in Appendix G. The observed bacteria loads are then added to the LDC plot as points. These points represent individual ambient water quality samples of bacteria. Points above the LDC indicate the bacteria instantaneous standard was exceeded at the time of sampling. Conversely, points under the LDC indicate the sample met the criterion.

The LDC approach recognizes that the assimilative capacity of a waterbody depends on the flow, and that maximum allowable loading varies with flow condition. Existing loading, and load reductions required to meet the TMDL water quality target can also be calculated under different flow conditions. The difference between existing loading and the water quality target is used to calculate the loading reductions required.

Table 4-2 presents the percent reduction goals necessary to achieve the contact recreation standard for select indicator bacteria for each 303(d) listed freshwater stream in the Study Area, as derived from the LDCs. Percent reduction goals for each 303(d)-listed freshwater stream in the Study Area are based on data analysis using the geometric mean criterion since it is anticipated that achieving the geometric mean over an extended period of time will likely ensure that the single sample criterion will also be achieved. Because the geometric mean criterion is considered more stringent, the TMDL for each of these sampling locations is determined by selecting the highest percent reduction goal calculated for the geometric mean criterion.

The sampling location requiring the highest percent reduction based on the geometric mean criterion was chosen for each freshwater stream. The most-downstream stations were found to require the highest percent reductions for all the segments within the Study Area.

The TMDL percent reduction goals for Halls Bayou below U.S. 59 (1006D_01), Halls Bayou above U.S. 59 (1006D_02), and Unnamed Tributaries of Halls Bayou (1006I_01) and (1006J_01) are based on the geometric mean criterion for *E. coli*.

The highest percent reductions for each stream are found in Table 4-2. The pollutant load allocations and percent reduction goals for each flow regime are summarized in Section 5.6. The highest percent reduction goals for each segment were all found to occur in the flow regime with the highest flows. The percent reduction goals under the highest flow conditions range from 95 to 99 percent. However, the overall percent reduction goal, which is calculated as the reduction required for the geometric mean of all the observed data to reach the geometric mean criterion, ranges from 87 to 94 percent.

Table 4-2 TMDL Percent Reductions Required to Meet Contact Recreation Standards in the Halls Bayou Watershed

Assessment Unit	Sampling Location	Stream Name	Indicator Bacteria Species	Highest Reduction		Overall Reduction
				Percent Reduction	Corresponding Flow Regime	
1006D_01	20023	Halls Bayou below U.S. 59	*E. coli*	99%	Highest flows	87%
1006D_02	11126	Halls Bayou above U.S. 59	*E. coli*	99%	Highest flows	94%
1006I_01	16666	Unnamed Tributary of Halls Bayou	*E. coli*	95%	Highest flows	89%
1006J_02	16665	Unnamed Tributary of Halls Bayou	*E. coli*	99%	Highest flows	93%

SECTION 5
TMDL CALCULATIONS

5.1 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. In other words, the facilities are required to meet instream criteria at their points of discharge. 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/2 * flow * unit conversion factor (#/day)*

Where:

criterion = 200 cfu/100mL, and 126 MPN/100 mL for fecal coliform, 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 indicator bacteria discharge limits and disinfection requirements of TPDES permits.

Storm water discharges from MS4 areas are considered permitted point sources. Therefore, the WLA calculations must also include an allocation for permitted storm water discharges. Given the limited amount of data available and the complexities associated with simulating rainfall runoff and the variability of storm water loading, a simplified approach for estimating the WLA_{MS4} areas was used in the development of these TMDLs. For the LDC 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 storm water contribution in the $WLA_{STORM\ WATER}$ component of the TMDL. The difference between the total storm water runoff load and the portion allocated to $WLA_{STORM\ WATER}$ constitutes the LA component of the TMDL (direct nonpoint runoff).

Table 5-1 Wasteload Allocations for TPDES-Permitted Facilities

Receiving Water	Assessment Unit	TPDES Number	NPDES Number	Facility Name	Permitted Flow (MGD)	*E. coli* Load (counts/day)
Halls Bayou below U.S. 59	1006D_01	12996-001	TX0096679	Aqua Utilities, Inc.	0.1	2.38E+08
		10495-016	TX0063053	City of Houston FWSD No. 23	7	1.67E+10
Halls Bayou above U.S. 59	1006D_02	01536-000	TX0007650	Ashbrook Corp.	0.004	9.54E+06
		10236-001	TX0021253	Sunbelt FWSD	0.45	1.07E+09
		10419-001	TX0070611	Nitsch & Son Utility Co. Inc.	0.25	5.96E+08
		10436-001	TX0032093	Champs Water Co.	0.15	3.58E+08
		10495-151	TX0075663	City of Houston	0.75	1.79E+09
		10518-001	TX0021261	Sunbelt FWSD	0.45	1.07E+09
		10610-001	TX0030988	Southern Water Corp.	0.475	1.13E+09
		10679-001	TX0023825	Harris County WCID 74	0.84	2.00E+09
		10812-001	TX0021270	Sunbelt FWSD	0.99	2.36E+09
		10825-001	TX0032255	Harvest Communities of Houston Inc.	0.023	5.48E+07
		11154-001	TX0023515	Mount Houston Road MUD	0.95	2.27E+09
		11231-001	TX0021245	Sunbelt FWSD	0.5	1.19E+09
		11255-001	TX0032034	Southwest Utilities Inc.	0.393	9.37E+08
		11473-001	TX0066478	Blue Bell Manor Utility Co. Inc.	0.6	1.43E+09
		11673-001	TX0063860	Woodloch MHP LLC	0.03	7.15E+07
		11807-001	TX0071820	Forest Hills MUD	0.8	1.91E+09
		11821-001	TX0072184	Johnson, Ana Araujo	0.05	1.19E+08
		12070-004	TX0100323	Aldine ISD	0.015	3.58E+07
		12083-001	TX0078883	Hooks Mobile Home Park Ltd.	0.06	1.43E+08
		12259-001	TX0084531	Bayou Forest Village Inc.	0.03	7.15E+07
		12261-001	TX0084671	Solhjou Houshang	0.04	9.54E+07
		12261-002	TX0119610	Solhjou Houshang	0.03	7.15E+07
		12399-001	TX0087785	Karbalai, Rita Laura Redow	0.05	1.19E+08
		12414-001	TX0088102	Woodgate Mobile Home Village Inc.	0.035	8.35E+07
		12555-001	TX0090492	Westfield Mhp Inc.	0.1	2.38E+08
		12882-001	TX0094986	Solhjou Bahram	0.03	7.15E+07
Halls Bayou above U.S. 59	1006D_02	12917-001	TX0095516	William Emmett Hartzog Jr.	0.006	1.43E+07
		12918-001	TX0095508	Hartzog, Linda Dianne	0.006	1.43E+07

Receiving Water	Assessment Unit	TPDES Number	NPDES Number	Facility Name	Permitted Flow (MGD)	*E. coli* Load (counts/day)
		13084-001	TX0097527	Mcculloch, Xiu Hui Li	0.025	5.96E+07
		13560-001	TX0107158	Lee, Jack Cheng	0.032	7.63E+07
		13609-001	TX0115797	Aldine ISD	0.042	1.00E+08
		13709-001	TX0103071	White Palace LP	0.01	2.38E+07
		13749-001	TX0122521	Afs Group Inc.	0.025	5.96E+07
		13767-001	TX0095656	Fatima Family Village Inc.	0.012	2.86E+07
		13770-001	TX0090735	Smith, William Donald	0.06	1.43E+08
		14156-001	TX0122190	Rex-Temple Inc.	0.003	7.15E+06
		14217-001	TX0123579	Karbalai, Laura Redow	0.02	4.77E+07
		14277-001	TX0124265	Ali Mohammad Solhjou	0.015	3.58E+07
		14620-001	TX0127949	Bahram Solhjou	0.07	1.67E+08
		10919-001	TX0021237	Fallbrook, UD	1.3	3.10E+09
		12919-001	TX0099171	Thomas, Tommy Joe	0.018	4.29E+07
		13211-001	TX0099104	Harris County MUD 321	0.8	1.91E+09
Unnamed Tributary of Halls Bayou	1006J_01	12772-001	TX0093572	5510 Acorn LLC	0.03	7.15E+07
		14001-001	TX0117692	Hartman, James William	0.004	9.54E+06
		14144-001	TX0120189	Ca New Plan Floating Rate Partnership LP	0.099	2.36E+08

5.2 Load Allocation

As discussed in Section 3, non-permitted 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 in part caused by 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:

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

Where:

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

5.3 Allocations for Future Growth

Compliance with each TMDL 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 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 2035 using population projections completed by HGAC.

Table 5-2 shows the population increases in each of the four TMDL assessment units based on the population projections from the H-GAC report (H-GAC 2007). The population increases range from 27 percent to 42 percent. The permitted flows were increased by the expected population growth per assessment unit between 2005 and 2035 to determine the estimated future flows. Future WWTF flows were calculated by multiplying the permitted flow by the increase in population estimated for each assessment unit. The future WWTF flows for each assessment unit were added to the flows from runoff to calculate the TMDL. The allocation for future population growth is the difference between the WWTF loads calculated using estimated future flows and permitted flows.

Table 5-2 Population Projection per Subwatershed

Stream Name	Assessment Unit	2005	2035	Increase
Halls Bayou below US 59	1006D_01	40,164	51,824	29%
Halls Bayou above US 59	1006D_02	95,599	121,775	27%
Unnamed Tributary of Halls Bayou	1006I_01	751	990	32%
Unnamed Tributary of Halls Bayou	1006J_01	9,256	13,143	42%

5.4 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.

These TMDLs incorporate an explicit MOS by setting a more stringent target for indicator bacteria loads 5 percent lower than the single sample criterion. The explicit MOS was used because of the limited amount of data for some of the sampling locations. For contact recreation, this equates to a single sample target of 374 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 TMDLs for the freshwater streams in this report incorporate an explicit MOS in each LDC by using 95 percent of the single sample criterion.

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 developing flow exceedance percentiles.

Seasonality analyses of *E. coli* datasets showed that while 70 percent of the stations (7 out of 10) exhibited higher geometric mean concentrations for the cooler months than the warmer months, there is no statistically significant difference in indicator bacteria between cool and warm weather seasons.

5.6 TMDL Calculations

The bacteria TMDLs for the 303(d)-listed WQM stations covered in this report were derived using LDCs. 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:

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

Tables 5-3 through 5-6 summarize the pollutant load allocations and percent reduction goals, for the median flow exceedance percentile of each of the three hydrologic classification categories. The percent reduction goals provided in the tables are derived from calculations using the geometric mean criterion not the single sample criterion. The estimated maximum allowable load of *E. coli* for each freshwater segment was determined as that corresponding to the regime requiring the highest load reduction (Tables 5-3 to 5-6).

The final TMDLs for the four assessment units included in this project are summarized in Table 5-7. The TMDLs were calculated based on the median flow in the 0-20 flow exceedance percentile range, which corresponds to the range requiring the highest percent reductions.

The final TMDL allocations needed to comply with the requirements of 40 CFR 130.7 are presented in Table 5-8. In this table the future capacity for WWTF has been added to the WLA_{WWTF}.

TMDL values and allocations in Table 5-8 are derived from calculations using the existing water quality criterion for *E. coli* and a critical flow condition (median flow of the hydrologic range requiring the greatest pollutant load reduction). However, designated uses and water quality criteria for these water bodies are subject to change through the TCEQ standards revision process. Figures 5-1 through 5-4 were developed to demonstrate how assimilative capacity, TMDL calculations and pollutant load allocations change in relation to a number of hypothetical water quality criteria for *E. coli*. The equations provided along with Figures 5-1 through 5-4 allow calculating new TMDLs and pollutant load allocations based on any potential new water quality criterion for *E. coli*.

Table 5-3 *E. coli* TMDL Calculations for Halls Bayou below U.S. 59 (1006D_01)

Station 20023			
Flow Regime %	**0%-20%**	**20%-80%**	**80%-100%**
Median Flow, Q (cfs)	127.0	23.89	11.69
Existing Load (10^9 org/day)	4.38E+04	1.72E+03	1.40E+01
Load Capacity at Current Flow (Q*126 org/dL) (10^9 org/day)	3.92E+02	7.36E+01	3.60E+01
MOS (Load Capacity*0.05) (10^9 org/day)	1.96E+01	3.68E+00	1.80E+00
Allowable Load at Water Quality Target and Current Flow (Load Capacity-MOS) (10^9 org/day)	3.72E+02	7.00E+01	3.42E+01
Load Reduction (10^9 org/day)	4.34E+04	1.65E+03	0.00E+00
Load Reduction (%)	**99.2%**	95.9%	0.0%
Overall Load Reduction	86.9%		
TMDL (Q_{future}*WQS) (10^9 org/day)	4.63E+02		

[a] *Includes loads from upstream segments addressed with separate LDCs*

Table 5-4 *E. coli* TMDL Calculations for Halls Bayou above U.S. 59 (1006D_02)

Station 11126			
Flow Regime %	**0%-20%**	**20%-80%**	**80%-100%**
Median Flow, Q (cfs)	79.6	14.0	7.8
Existing Load (10^9 org/day)	3.18E+04	3.98E+02	3.22E+02
Load Capacity at Current Flow (Q*126 org/dL) (10^9 org/day)	2.45E+02	4.32E+01	2.40E+01
MOS (Load Capacity*0.05) (10^9 org/day)	1.23E+01	2.16E+00	1.20E+00
Allowable Load at Water Quality Target and Current Flow (Load Capacity-MOS) (10^9 org/day)	2.33E+02	4.10E+01	2.28E+01
Load Reduction (10^9 org/day)	3.15E+04	3.57E+02	2.99E+02
Load Reduction (%)	**99.3%**	89.7%	92.9%
Overall Load Reduction (%)		94%	
TMDL (Q_{future}*WQS) (10^9 org/day)	2.80E+02		

Table 5-5 *E. coli* TMDL Calculations for Unnamed Tributary of Halls Bayou (1006I_01)

Station 16666			
Flow Regime %	**0%-20%**	**20%-80%**	**80%-100%**
Median Flow, Q (cfs)	0.9	0.09	0.03
Existing Load (10^9 org/day)	5.05E+01	2.61E+00	5.00E-01
Load Capacity at Current Flow (Q*126 org/dL) (10^9 org/day)	2.72E+00	2.75E-01	8.45E-02
MOS (Load Capacity*0.05) (10^9 org/day)	1.36E-01	1.37E-02	4.23E-03
Allowable Load at Water Quality Target and Current Flow (Load Capacity-MOS) (10^9 org/day)	2.58E+00	2.61E-01	8.03E-02
Load Reduction (10^9 org/day)	4.79E+01	2.35E+00	4.19E-01
Load Reduction (%)	**94.9%**	90.0%	83.9%
Overall Load Reduction (%)		89%	
TMDL (Q_{future}*WQS) (10^9 org/day)	2.72E+00		

Table 5-6 *E. coli* TMDL Calculations for Unnamed Tributary of Halls Bayou (1006J_01)

Station 16665			
Flow Regime %	**0%-20%**	**20%-80%**	**80%-100%**
Median Flow, Q (cfs)	8.2	0.85	0.28
Existing Load (10^9 org/day)	2.06E+03	3.88E+01	4.83E+00
Load Capacity at Current Flow (Q*126 org/dL) (10^9 org/day)	2.52E+01	2.61E+00	8.57E-01
MOS (Load Capacity*0.05) (10^9 org/day)	1.26E+00	1.30E-01	4.29E-02
Allowable Load at Water Quality Target and Current Flow (Load Capacity-MOS) (10^9 org/day)	2.40E+01	2.48E+00	8.14E-01
Load Reduction (10^9 org/day)	2.04E+03	3.63E+01	4.01E+00
Load Reduction (%)	**98.8%**	93.6%	83.1%
Overall Load Reduction (%)		93%	
TMDL (Q_{future}*WQS) (10^9 org/day)	2.61E+01		

Table 5-7 *E. coli* TMDL Summary Calculations for Halls Bayou Assessment Units

Assessment Unit	Sampling Location	Stream Name	TMDL[a] (counts/day)	WLA_{WWTF}[b] (counts/day)	WLA_{MS4}[d] (counts/day)	LA[e] (counts/day)	MOS[f] (counts/day)	Future Growth[g] (counts/day)
1006D_01	20023	Halls Bayou below U.S. 59	4.63E+11	4.27E+10[c]	3.82E+11	3.40E+09	2.32E+10	1.20E+10
1006D_02	11126	Halls Bayou above U.S. 59	2.80E+11	2.54E+10	2.33E+11	0	1.40E+10	6.94E+09
1006I_01	16666	Unnamed Tributary of Halls Bayou	2.72E+09	0	2.15E+09	4.35E+08	1.36E+08	0
1006J_01	16665	Unnamed Tributary of Halls Bayou	2.61E+10	3.17E+08	2.44E+10	0	1.31E+09	1.33E+08

[a] *Maximum allowable load for the flow range requiring the highest percent reduction (Tables 5-3 to 5-6)*
[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 5-1)*
[c] *The WLA_{WWTF} for 1006D_01 includes all the facilities discharging upstream of the TMDL station. Thus, this allocation includes WWTF that discharge to other AUs. Individual allocations are provided in Table 5-1*
[d] *$WLA_{STORM\ WATER}$ = (TMDL – MOS –WLA_{WWTF})*(percent of drainage area covered by storm water permits)*
[e] *LA = TMDL – MOS –WLA_{WWTF} –$WLA_{STORM\ WATER}$-Future growth*
[f] *MOS = TMDL x 0.05*
[g] *Projected increase in WWTF permitted flows*126/2*conversion factor*

Table 5-8 Final TMDL Allocations

Assessment Unit	TMDL (MPN/day)	WLA_{WWTF}[a] (MPN/day)	$WLA_{STORM\ WATER}$ (MPN/day)	LA (MPN/day)	MOS (MPN/day)
1006D_01	4.63E+11	5.46E+10	3.82E+11	3.40E+09	2.32E+10
1006D_02	2.80E+11	3.23E+10	2.33E+11	0	1.40E+10
1006I_01	2.72E+09	0	2.15E+09	4.35E+08	1.36E+08
1006J_01	2.61E+10	4.50E+08	2.44E+10	0	1.31E+09

[a] *WLA_{WWTF}= $WLA_{WWTF\ (Table\ 5\text{-}7)}$ + Future $Growth_{(Table\ 5\text{-}7)}$*

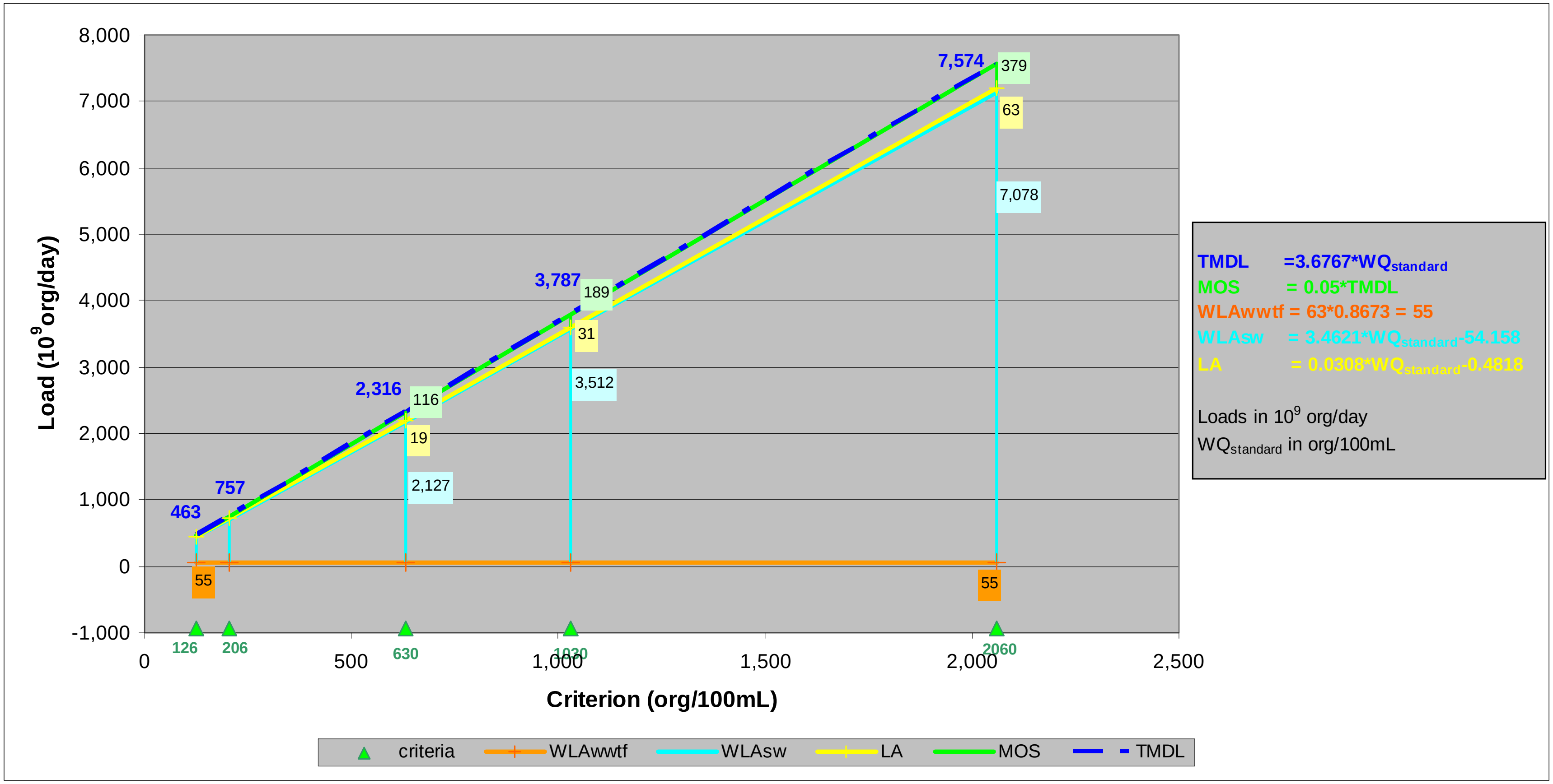


Figure 5-1 Allocation Loads for AU 1006D_01 as a Function of WQ Criteria

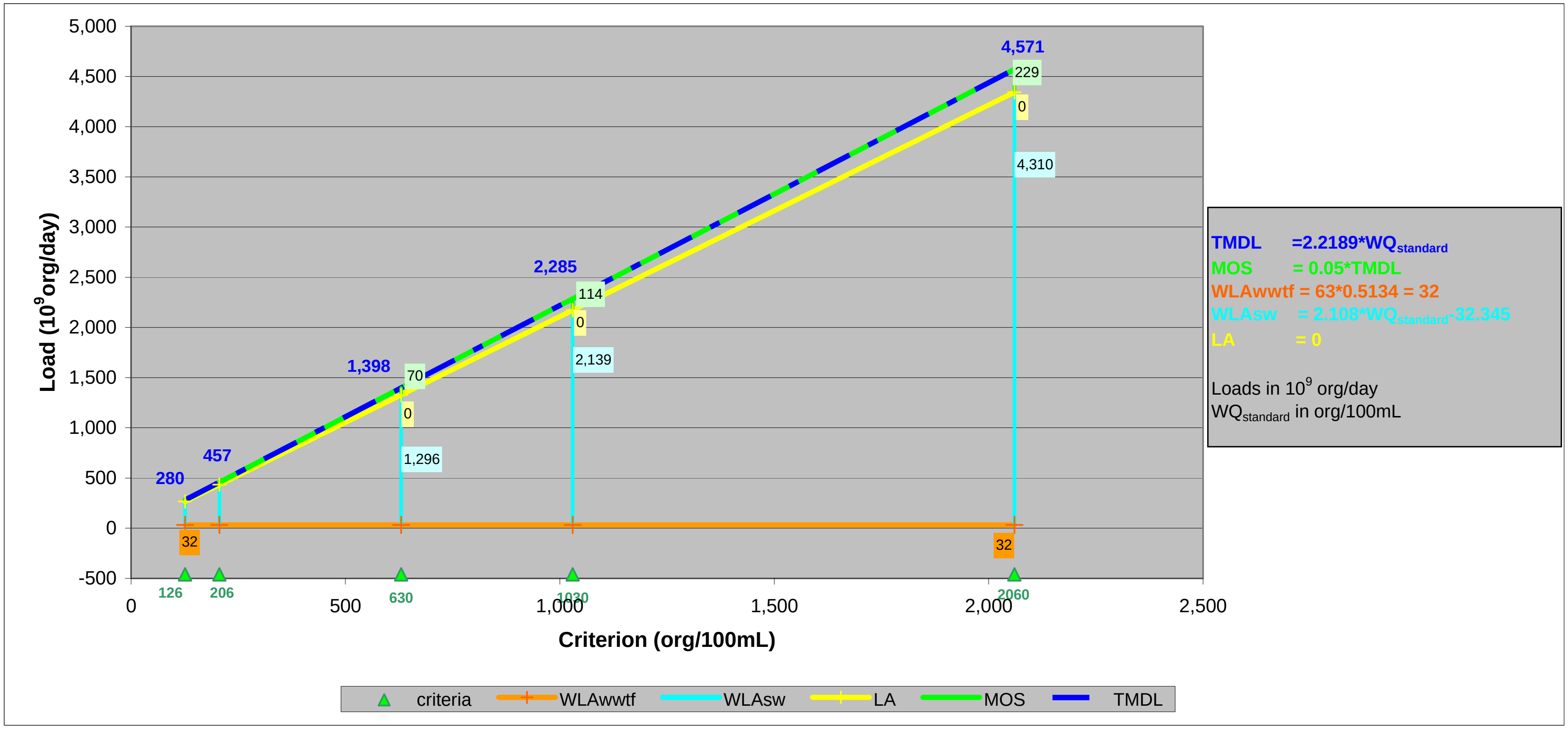


Figure 5-2 Allocation Loads for AU 1006D_02 as a Function of WQ Criteria

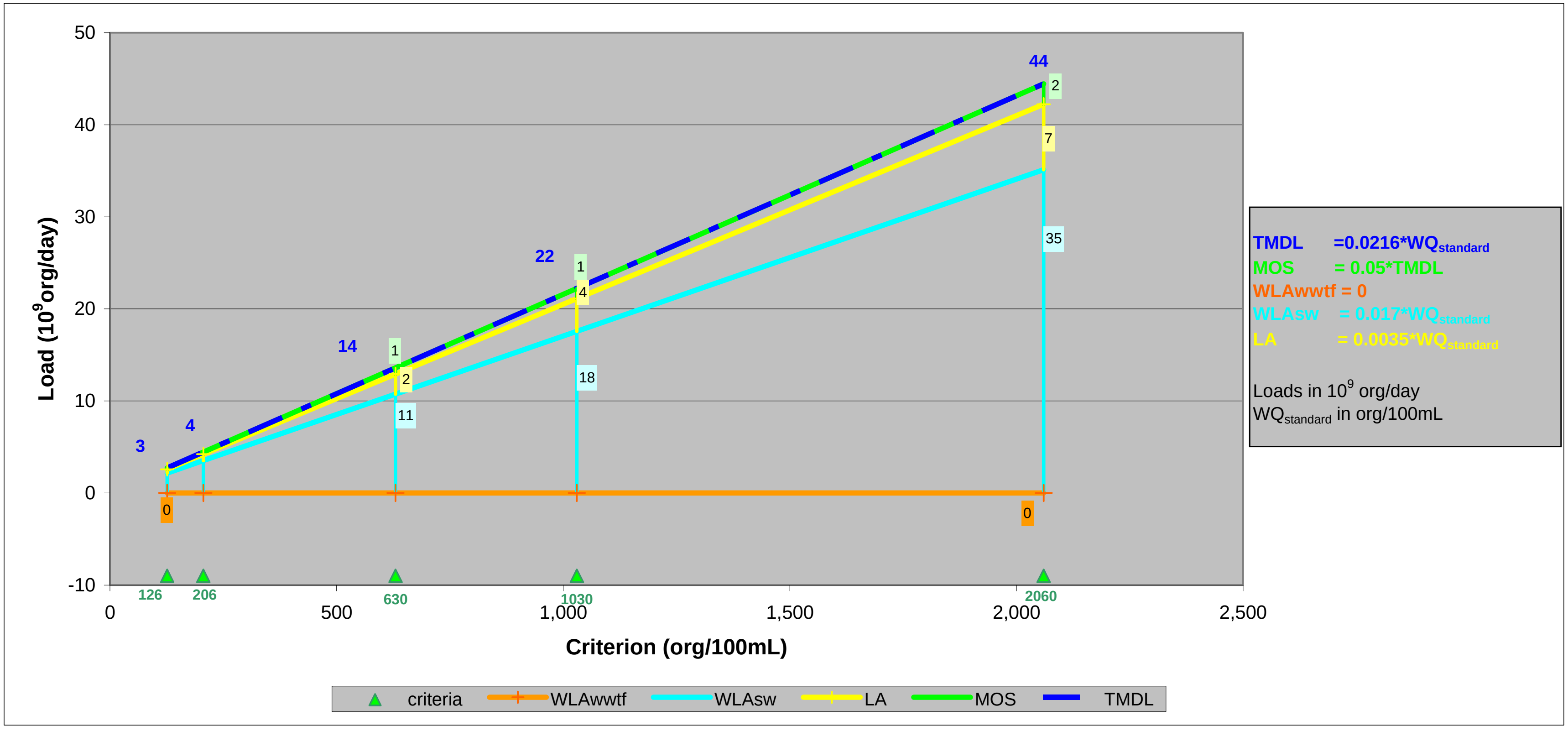


Figure 5-3 Allocation Loads for AU 1006I_01 as a Function of WQ Criteria

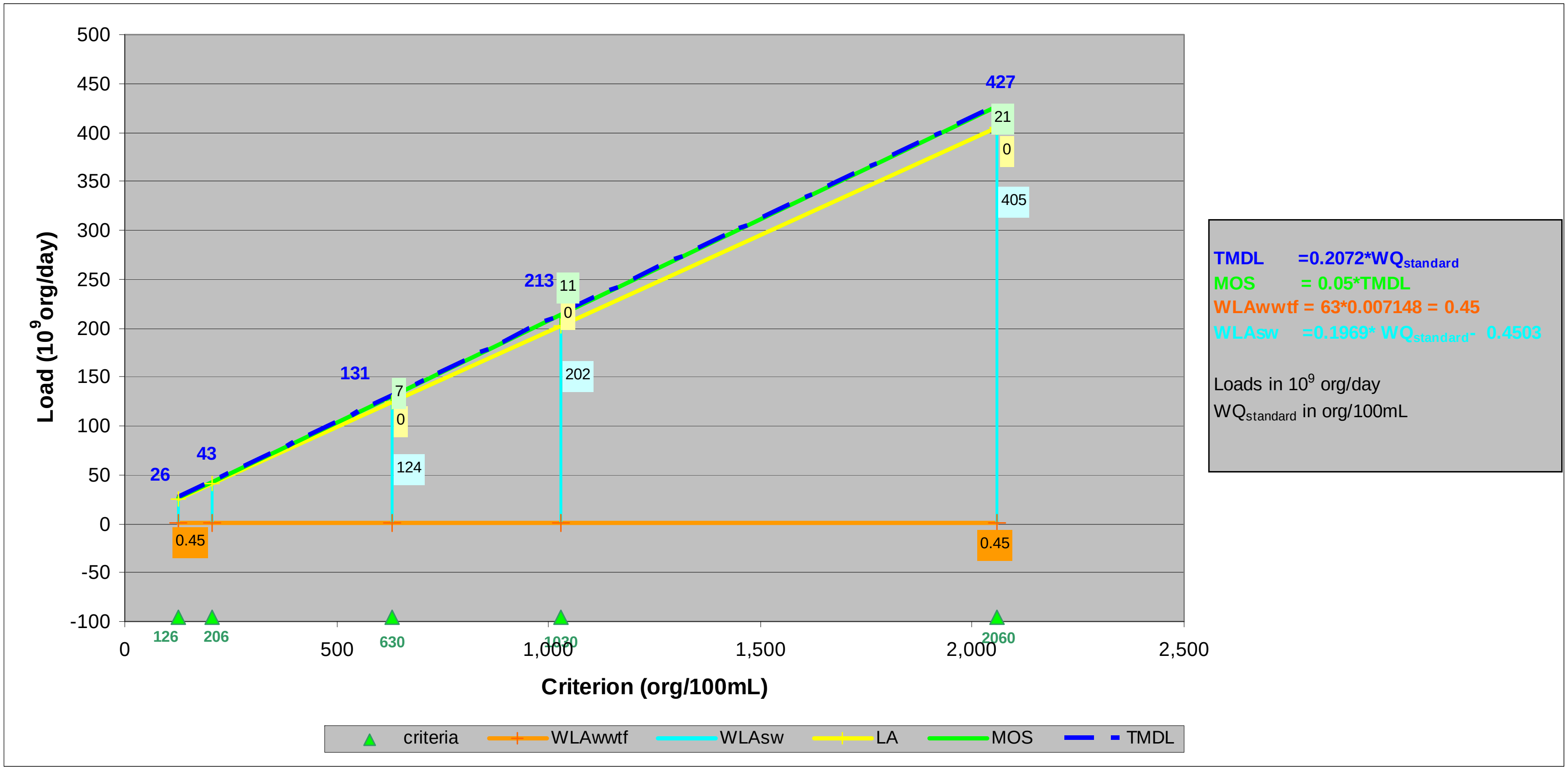


Figure 5-4 Allocation Loads for AU 1006J_01 as a Function of WQ Criteria

SECTION 6
PUBLIC PARTICIPATION

The Houston-Galveston Area Council is providing coordination for public participation in this project. To obtain public input on the Halls Bayou Bacteria TMDL and the implementation phase, public meetings were held on October 19, 2007 and November 10, 2008. These meetings introduced the TMDL process, identified the impaired segments and the reason for the impairment, reviewed historical data, and described potential sources of bacteria within the watershed. In addition, the meetings gave TCEQ the opportunity to solicit input from all interested parties within the Study Area.

SECTION 7
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APPENDIX A
AMBIENT WATER QUALITY BACTERIA DATA – 1992 TO 2008

(Electronic)

APPENDIX B
FLOW DATA

(Electronic)

APPENDIX C
DISCHARGE MONITORING REPORTS FOR FLOW – 1997 TO 2007

(Electronic)

APPENDIX D
DISCHARGE MONITORING REPORTS FOR FECAL COLIFORM – 1998 TO 2004

(Electronic)

APPENDIX E
SANITARY SEWER OVERFLOWS DATA SUMMARY – 2001 TO 2003

(Electronic)

APPENDIX F
GENERAL METHODS FOR ESTIMATING FLOW AT WQM STATIONS

Appendix F
General Methods for Estimating Flow at WQM Stations

Flow duration curve analysis looks at the cumulative frequency of historic flow data over a specified period (USEPA 2007). Because stream flow conditions on any given day can be highly variable, depending on watershed characteristics and weather patterns, flow duration curves are a useful tool for characterizing the percentage of days in a year when given flows occur (USEPA 2007). To support the development of bacteria TMDLs, flow duration curves can be developed using existing USGS measured flow where the data exist at the same location as the WQM station, or by estimating flow for WQM stations with no corresponding flow record. Flow data are derived and synthesized to support preparation of flow duration curves and load duration curves for each WQM station in this report in the following priority.

USGS Gage Coincides with WQM Station

In cases where a USGS flow gage coincides with, or occurs within one-half mile upstream or downstream of the WQM station the following protocols will be employed:

a. If simultaneous daily flow data matching the water quality sample date are available, these flow measurements will be used to prepare flow exceedance percentiles.
b. If flow measurements at the coincident gage are missing for some dates on which water quality samples were collected, the gaps in the flow record will be filled, or the record will be extended, by estimating flow based on measured streamflows at a nearby gages. First, the most appropriate nearby stream gages are identified as those within a 150 km radius that have at least 300 coincident daily flow measurements. For all identified gages, four regression equations are calculated on the coincident data. The calculated regressions include a linear regression, log-linear regression, logarithmic regression and a power curve regression. For each regression, the root mean square error (RMSE) is calculated and the equation with the best fit or lowest RMSE is chosen to represent that gage. The gages are ranked in order of best fit or increasing RMSE. As many data points requiring filling as possible are filled with the best fit gage (lowest RMSE). If dates remain to be filled, the process is repeated in an iterative fashion with the second best fit gage and so forth until all dates requiring filling have been filled.

No USGS Gage Coincides with WQM Station

Where no coincident flow data are available for a WQM station, but flow gage(s) are present upstream and/or downstream, flows will be estimated for the WQM station from an upstream or downstream gage using a watershed area ratio method that includes a modification utilizing the NRCS Curve number (CN) to account for differences in watersheds (Wurbs & Sisson, 1999; Wurbs 2006). In coastal watersheds, where the choice of using an upstream or downstream station may be severely limited, it may be necessary to use a gage station from an adjacent watershed that has similar characteristics. These recent studies have demonstrated that, while flow predictions for a specific time with any flow distribution method are not highly accurate, RMSE, means and others flow characteristics can be estimated with an acceptable degree of accuracy. Since many of the flow frequencies important to a load duration curve involve the low end of the frequency range and the NRCS Curve method involves inherent limitations as flows approach the initial abstraction limit, another modification was applied to this method.

The Furness method (Furness 1959) employed by the USGS in Kansas (Studley 2000) estimates flow duration curves by estimating several descriptive statistics that describe the curve. The adaptation was included to utilize the existing period of record to calculate the flow frequency curve for an individual USGS gage, which completely describes the shape of the curve. The mean flow is then projected to the ungaged location utilizing the modified NRCS Curve method, which operates best around the mean of a distribution. Individual flow measurements and flow frequencies can then be projected to the ungaged location by normalizing them to the percent of the mean flow and multiplying the result by the newly projected mean flow for the ungaged location.

Drainage subbasins will first be delineated for all impaired 303(d)-listed WQM stations, along with all USGS flow stations located in the 8-digit HUCs with impaired streams. All the USGS gage stations will be identified that have a continuous period of record upstream and downstream of the subwatersheds with 303(d) listed WQM stations.

a. Watershed delineations are performed using ESRI Arc Hydro with a 30 meter resolution National Elevation Dataset (NED) digital elevation model, and National Hydrography Dataset (NHD) streams. The area of each watershed will be calculated following watershed delineation.
b. The watershed average curve number is calculated from soil properties and land cover as described in the U.S. Department of Agriculture (USDA) Publication TR-55: Urban Hydrology for Small Watersheds. The soil hydrologic group is extracted from NRCS STATSGO soil data, and land use category from the NOAA Coastal Change Analysis Program (C-CAP). Based on land use and the hydrologic soil group, SCS curve numbers are estimated at the 30-meter resolution of the C-CAP grid as shown in Table F-1.
c. The average curve number is then calculated from all the grid cells within the delineated watershed.
d. The average rainfall is calculated for each watershed from average annual precipitation datasets for the period 1988-2007 from rainfall data obtained from Harris County Office of Emergency Management.

Table F-1 Runoff Curve Numbers for Various Land Use Categories and Hydrologic Soil Groups

C-CAP Value	C-CAP Class	Group A	Group B	Group C	Group D
2	High-Intensity Developed	89	92	94	95
3	Medium-Intensity Developed	77	85	90	92
4	Low-Intensity Developed	61	75	83	87
5	Open-Space Developed	39	61	74	80
6	Cultivated Land	67	78	85	89
7	Pasture/Hay	35	56	70	77
8	Grassland/Herbaceous	39	61	74	80
9	Deciduous Forest	30	55	70	77
10	Evergreen Forest	30	55	70	77
11	Mixed Forest	30	55	70	77
12	Scrub/Shrub	30	48	65	73
13	Palustrine Forested Wetland	0	0	0	0
14	Palustrine Scrub/Shrub Wetland	0	0	0	0
15	Palustrine Emergent Wetland	0	0	0	0
16	Estuarine Forested Wetland	0	0	0	0
17	Estuarine Scrub/Shrub Wetland	0	0	0	0
18	Estuarine Emergent Wetland	0	0	0	0
19	Unconsolidated Shore	0	0	0	0
20	Bare Land	77	86	91	94
21	Water	0	0	0	0
22	Palustrine Aquatic Bed	0	0	0	0
23	Estuarine Aquatic Bed	0	0	0	0

e. The mean flow at the ungaged site is calculated from the gaged site utilizing the modified NRCS Curve Number method (Wurbs & Sisson, 1999). The NRCS runoff curve number equation is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (1)$$

where:

Q = runoff (inches)

P = rainfall (inches)

S = potential maximum retention after runoff begins (inches)

I_a = initial abstraction (inches)

If $P < 0.2$, $Q = 0$. Initial abstraction has been found to be empirically related to S by the equation

$$I_a = 0.2*S \qquad (2)$$

Thus, the runoff curve number equation can be rewritten:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (3)$$

S is related to the curve number (CN) by:

$$S = \frac{1000}{CN} - 10 \qquad (4)$$

f. First, S is calculated from the average curve number for the gaged watershed. Next, the historic mean flow at the gage is converted to depth basis (as used in equations 1 and 3) by dividing by its drainage area, then converted to inches. Equation 3 is then solved for daily precipitation depth of the gaged site, P_{gaged}. The daily precipitation depth for the ungaged site is then calculated as the precipitation depth of the gaged site multiplied by the ratio of the long-term average precipitation in the watersheds of the ungaged and gaged sites:

$$P_{ungaged} = P_{gaged}\left(\frac{M_{ungaged}}{M_{gaged}}\right) \qquad (5)$$

where M is the mean annual precipitation of the watershed in inches. The daily precipitation depth for the ungaged watershed, along with the average curve number of the ungaged watershed, are then used to calculate the depth equivalent daily flow Q of the ungaged site. Finally, the volumetric flow rate at the ungaged site is calculated by multiplying by the area of the watershed of the ungaged site and converting the value to cubic feet.

g. If wastewater treatment facilities (WWTF) are located within the drainage area of the USGS gage, a base flow for the USGS gage should be calculated before projecting flow to an ungaged site. The base flow for the USGS gage is calculated by deducting the sum of the Average Monthly WWTF flow for all outfalls in the drainage area from the measured USGS flow record. The Average Monthly WWTF flows are applied for each day (1-31) of a given month.

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

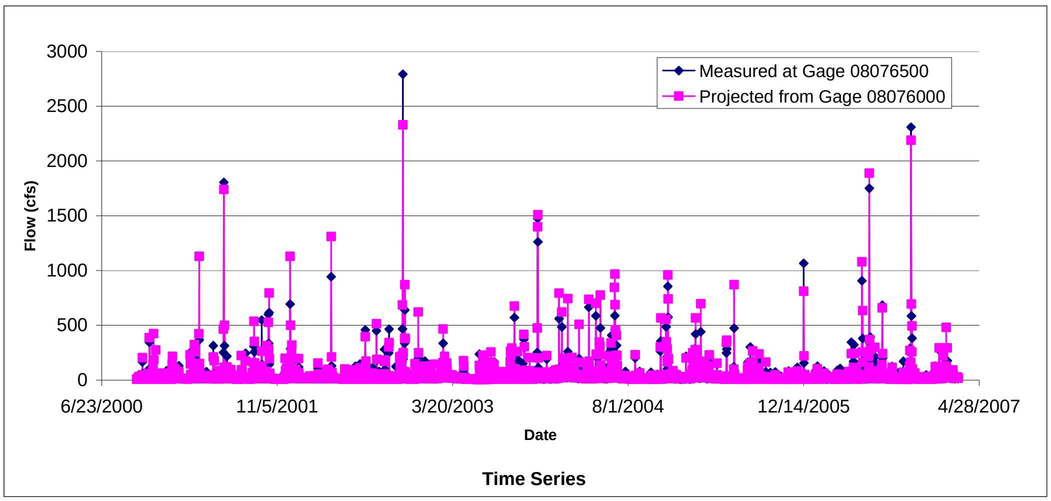
If the base flow results in a negative value, that value is then set to zero.

h. After flow has been estimated for the ungaged site, average monthly flows from WWTFs that drain into the ungaged watershed are then added to the flow estimates.

In the rare case where no coincident flow data are available for a WQM station <u>and</u> no gages are present upstream or downstream, flows will be estimated for the WQM station from a gage on an adjacent watershed of similar size and properties, via the same procedure described above for upstream or downstream gages.

Verification of Projected Flow for Halls Bayou

Daily flow data were available at USGS gage station 08076500 (Halls Bayou at Houston, TX, Texas) for the time period 10/1/2000 to present. Therefore, the flow projection tool was used to obtain a flow series that could be compared to the available data for gage 08076500. For the Halls Bayou Watershed, the gage used for flow projections was 08076000 (Greens Bayou near Houston, Texas). Figure F-1 presents a comparison of the measured flows and the projected flows. As can be seen, there is good agreement between the flows. Thus, it is expected that projected flows be representative of conditions in halls Bayou.



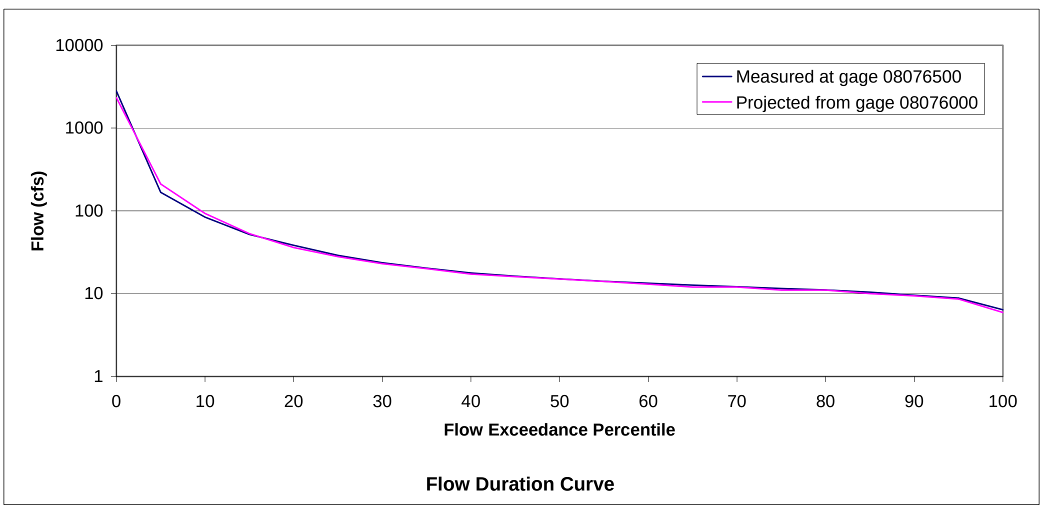


Figure F-1 Flow Projections for Halls Bayou

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APPENDIX G
FLOW EXCEEDANCE PERCENTILES FOR TMDL WQM STATIONS

(Electronic)