TECHNICAL SUPPORT DOCUMENT: BACTERIA TOTAL MAXIMUM DAILY LOAD FOR THE MARY'S CREEK BYPASS WATERSHED, HOUSTON, TEXAS
(1102F_01)

Prepared for:

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

TCEQ

Prepared by:

University of Houston

August 2016

TECHNICAL SUPPORT DOCUMENT: BACTERIA TOTAL MAXIMUM DAILY LOAD FOR MARY'S CREEK BYPASS IN THE CLEAR CREEK WATERSHED, HOUSTON, TEXAS

(1102F_01)

Contract No. 582-14-42708

Work Order No. 05

Prepared for:

TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

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AUGUST 2016

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ACRONYMS AND ABBREVIATIONS

ASAE	American Society of Agricultural Engineers
BASINS	Better Assessment Science Integrating Point & Non-point Sources
C-CAP	Coastal Change Analysis Program
CAFO	Concentrated animal feeding operation
CFR	Code of Federal Regulations
cfs	Cubic feet per second
counts	Colony forming unit
CN	Curve number
dL	Deciliter
DMR	Discharge monitoring report
E coli	Escherichia coli
EPA	Environmental Protection Agency
FDC	Flow duration curve
GCHD	Galveston County Health District
GIS	Geographic information system
HCFCD	Harris County Flood Control District
HCOEM	Harris County Office of Emergency Management
H-GAC	Houston-Galveston Area Council
LA	Load allocation
LDC	Load duration curve
mL	Milliliter
MOS	Margin of safety
MPN	Most probable number
MS4	Municipal separate storm sewer system

NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
NRCS	National Resources Conservation Service
OSSF	On-site sewage facility
RMSE	Root mean square error
SSO	Sanitary sewer overflow
SWQS	Surface water quality standards
SWQMIS	Surface Water Quality Monitoring Information System
TAC	Texas Administrative Code
TCEQ	Texas Commission on Environmental Quality
TMDL	Total Maximum Daily Loads
TPDES	Texas Pollution Discharge Elimination System
TSARP	Tropical Storm Allison Recovery Project
TWDB	Texas Water Development Board
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	Waste load allocation
WQM	Water quality monitoring
WQS	Water quality standard
WWTF	Wastewater treatment facility

CHAPTER 1
INTRODUCTION

1.1 Watershed Description

Mary's Creek Bypass (Segment 1102F), which is shown in Figure 1-1, is a small flood control diversion of Mary's Creek (Segment 1102B). It branches off of Mary's Creek, avoids a flood prone area, then rejoins Mary's Creek downstream. Mary's Creek (1102_B) itself is a small portion of the Clear Creek watershed, which empties into Clear Lake, which empties into Galveston Bay. The TMDL area is 2.37 miles long and has a drainage area of 2.05 square miles.

In yearb2008, TMDLs were developed for impairments to contact recreational use for indicator bacteria in the Clear Creek watershed, which included segments 1101, 1101B, 1101D, 1102, 1102A, 1102B, 1102C, 1102D, and 1102E, and in year 2012, a TMDL was developed for additional segments 1101A, 1101C, 1101E, and 1102G. This Technical Support Document (TSD) focuses on the following waterbody that is designated as Category 5a [303(d) list] in the 2014 Integrated Report for nonsupport of contact recreation use:

- Mary's Creek Bypass (1102F): From the Mary's Creek confluence NE of FM 518 to a point 0.96 km (0.60 mi) upstream to the Mary's Creek confluence (NW of County Road 126).

The delineation of each subwatershed is derived from 2005 geographic information system (GIS) data files created for the Tropical Storm Allison Recovery Project (TSARP), provided by Harris County Flood Control District (HCFCD). The TSARP catchment encompasses both Mary's Creek Bypass and a portion of Mary's Creek main channel. EPA's BASINS watershed delineation tool was employed to further delineate the catchment into drainage areas for 1102B and 1102F. The impaired waterbody and its surrounding watershed 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 (USACE 1985). The average maximum daytime temperature is 34 degrees Celsius (93 degrees Fahrenheit) while the temperature averages between 4 and 16 degrees Celsius (39 to 61 degrees Fahrenheit) during the winter. Summer rainfall is dominated by sub-tropical convection, winter rainfall by frontal storms, and fall and spring months by combinations of these two (Burian 2005).

The Study Area experiences frequent rainfall events with annual precipitation totals around 50 inches. Monthly rainfall totals are fairly consistent throughout the year, with slightly more rainfall falling in May and June (approximately 5 inches), compared to the remainder of the year (3 to 4 inches). High intensity rainfall often causes localized street flooding and occasional out of bank conditions. As the study watershed is located near the Gulf Coast, they are potentially subject to hurricanes generally between June 1 and November 30, although the chance of tropical weather declines dramatically in October.

Table 1-1, derived from the 2000 and 2010 U.S. Census, demonstrates that the county in which the watershed is located is very densely populated. Table 1-1 also shows population growth for Brazoria and Galveston Counties (U.S. Census Bureau 2010). Friendswood and Pearland are the two cities whose limits lie within the Study Area and are anticipated to grow by 23% and 37% respectively, according to the Texas Water Development Board (TWDB). Table 1-2 lists TWDB population growth estimates from 2010 to 2030. Population estimates for the Study Area, derived from the 2010 Census are provided in Table 1-3.

Table 1-1: County Population and Density

County Name	2010 U.S. Census	2010 Population Density (per square mile)
Brazoria	313,166	230.7
Galveston	291,309	769.9

Table 1-2: Mary's Creek Bypass Watershed Population Increases by City, 2010 to 2030

City	2010 Census Population	2020 Population Estimate	2030 Population Estimate	Growth Rate (2010-2030)
Friendswood	35,805	39,649	44,049	23%
Pearland	91,252	115,164	125,231	37%

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

Table 1-3: Population Estimate by Assessment Unit

Segment Name	Assessment Unit	2010 Census Population Estimate	2010 Census Household Count
Mary's Creek Bypass	1102F_01	**6,820**	**2,433**

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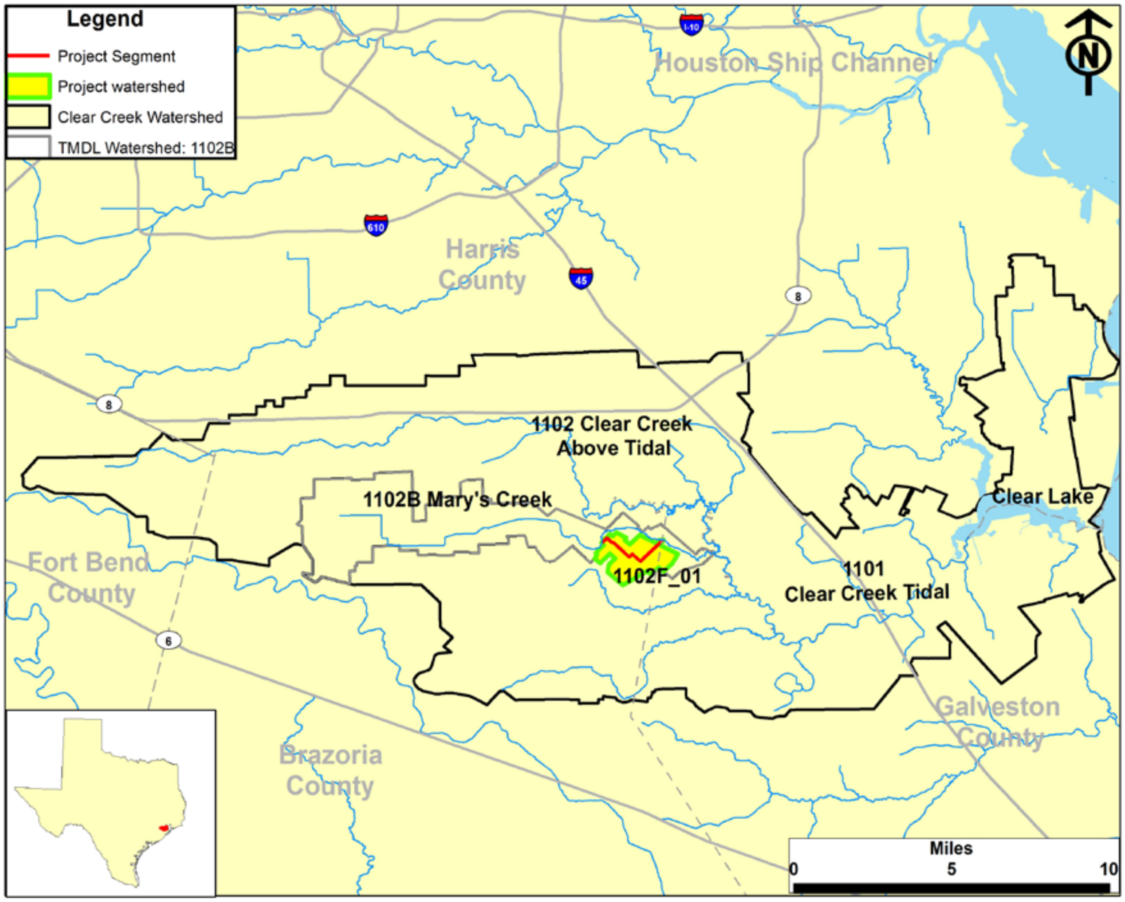

Figure 1-1: Location Map for Mary's Creek Bypass in the Clear Creek Watershed

1.2 Summary of Existing Data

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

1.2.1 Soil

The geology of the Clear Creek Watershed comprises unconsolidated clay, clay shale, and poorly cemented sand that extend several miles in depth (TCEQ 2005). The soil has a low water-bearing capacity, high moisture content, low permeability, and a high shrink-swell potential. The USDA National Resources Conservation Service (NRCS, 2015) information was used to characterize soil in the Study Area. As can be observed in Figure 1-2, the soil types that dominate the watershed are from the Bernard clay and Lake Charles clay soil series. Table 1-4 lists the distribution and attributes of the five soil series found in the Study Area.

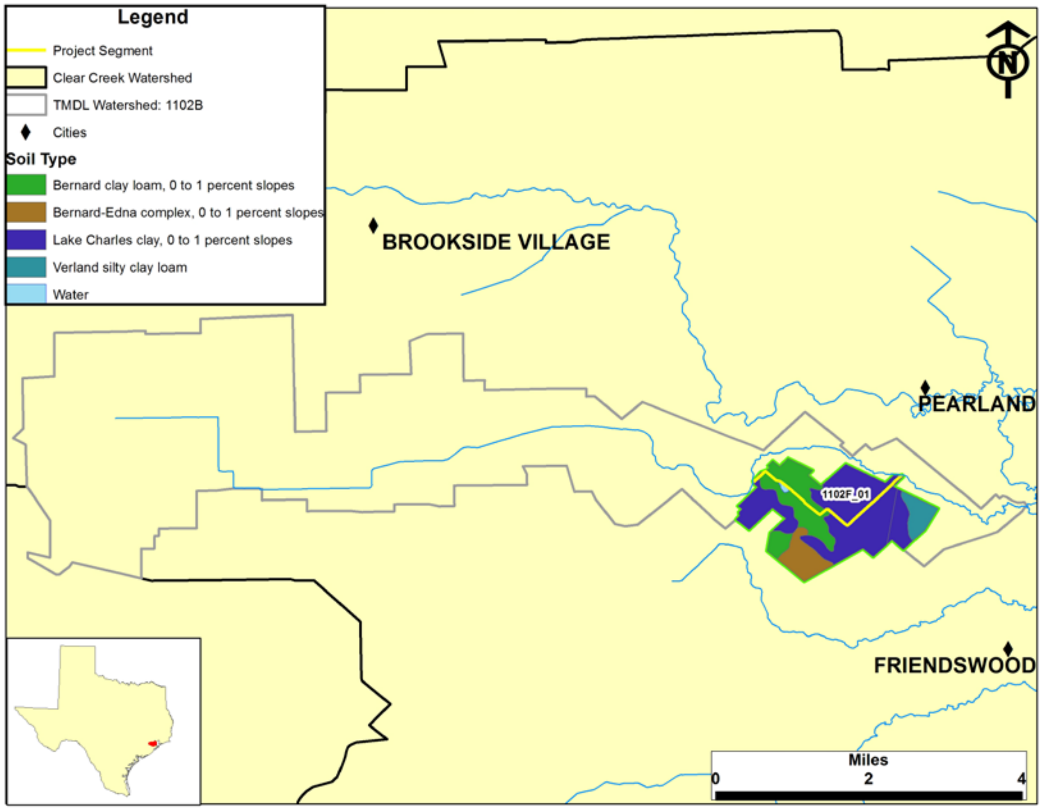

Figure 1-2: Mary's Creek Bypass Region Soil Types

Table 1-4: Characteristics of Soil Types in Mary's Creek Bypass

All information derived from NCRS data: http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

NRCS Soil Type	Surface Texture	Soil Series Name	Hydro-logic Soil Group	Soil Drainage Class	Average Available Water Storage (cm)	Percent of Watershed Area
TX167	Silty clay loam	Verland silty clay loam	D	Somewhat poorly drained	26.44	6.43%
TX167	Clay	Lake Charles clay, 0 to 1 percent slopes	D	Moderately well drained	36.54	6.12%
TX039	Clay	Lake Charles clay, 0 to 1 percent slopes	D	Moderately well drained	36.54	53.06%
TX039	Clay loam	Bernard clay loam, 0 to 1 percent slopes	D	Somewhat poorly drained	34.43	24.22%
TX039	Clay loam	Bernard-Edna complex, 0 to 1 percent slopes	D	Somewhat poorly drained	29.47	9.87%

1.2.2 Land Cover

Table 1-5 summarizes the acreages and the corresponding percentages of the land use categories within the Study Area. The land cover data were retrieved from the National Oceanic and Atmospheric Administration (2011) land cover database obtained from Houston-Galveston Area Council. The total acreage of each land cover/land use type in Table 1-5 corresponds to the watershed delineation in Figure 1-3. The predominant land use/land cover category in this watershed is developed land (89% as the sum of all developed classes), followed by herbaceous (4%) and forest (3.7%).

Table 1-5: Aggregated Land Use/Land Cover Summaries by Type

Aggregated Land Cover Category	Area (ac)	Percent (%)
Open Water	4.0	0.31%
Developed, Open Space	384.8	29.38%
Developed, Low Intensity	395.7	30.21%
Developed, Medium Intensity	378.5	28.90%
Developed, High Intensity	31.4	2.40%
Barren Land	0.2	0.02%
Deciduous Forest	28.3	2.16%
Evergreen Forest	15.8	1.21%
Mixed Forest	4.0	0.31%
Shrub/Scrub	1.8	0.14%
Herbaceous	57.5	4.39%
Hay/Pasture	4.7	0.36%
Woody Wetlands	2.9	0.22%

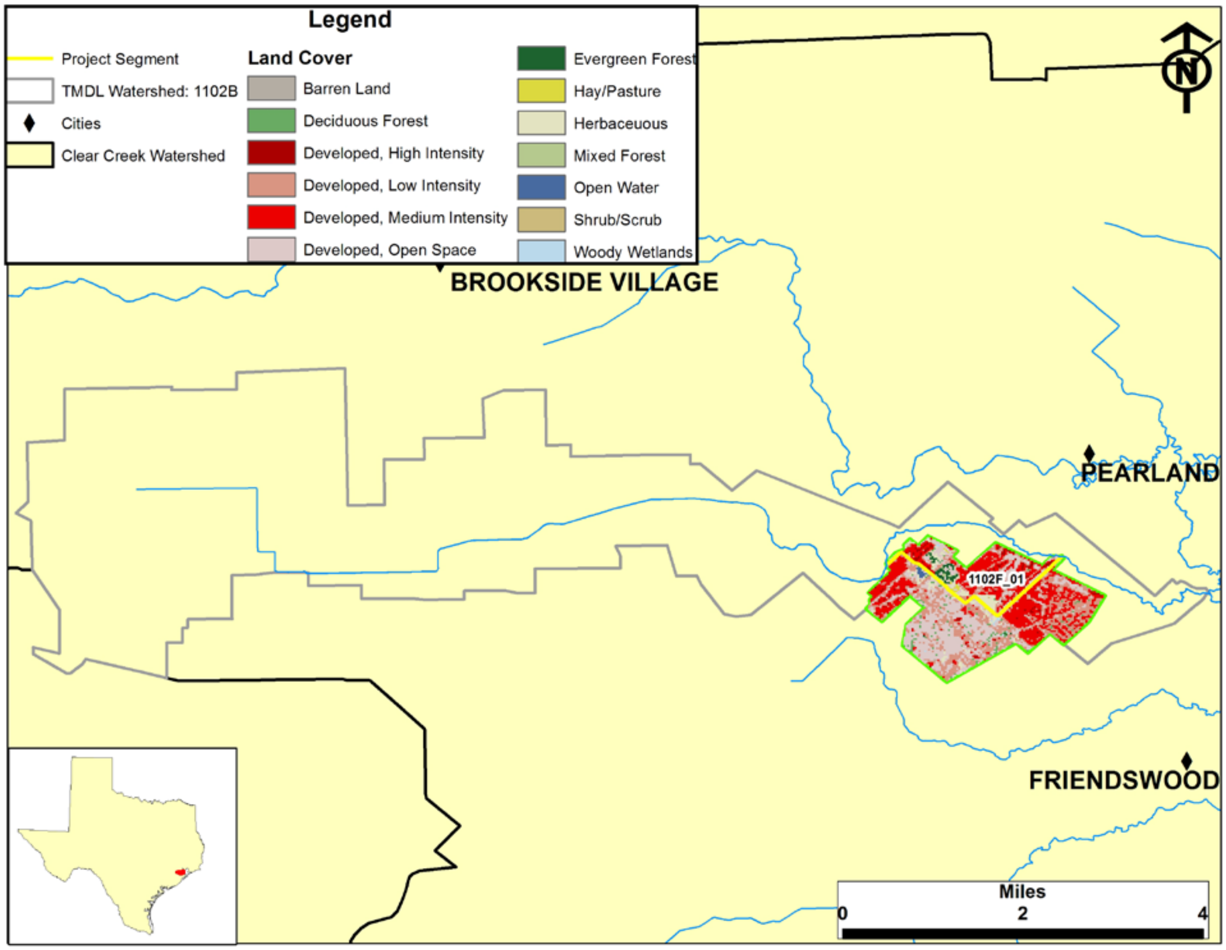

Figure 1-3: Land use/ Land Cover Map for Mary's Creek Bypass

1.2.3 Precipitation

There are no rain gages currently in operation directly within the Study Area; however, three gages (Figure 1-4) within reasonable distance were used in this study. The Harris County Office of Homeland Security and Emergency Management (HCOEM) maintain the gages.

Table 1-6 summarizes total annual rainfall for the three gages for a 10-year period. The region has high levels of humidity and receives annual precipitation ranging between 47.8 and 53.8 inches per year as shown in Table 1-6. Based on data for the period 2005 to 2015, the local average rainfall is around 51.1 inches per year.

To evaluate the distribution of rainfall across the watershed, Thiessen polygons were developed for each rainfall gage as shown in Figure 1-4. Average rainfall by subwatershed was also calculated and summarized in Table 1-7. The average rainfall amount in the Study Area was 52.5 inches.

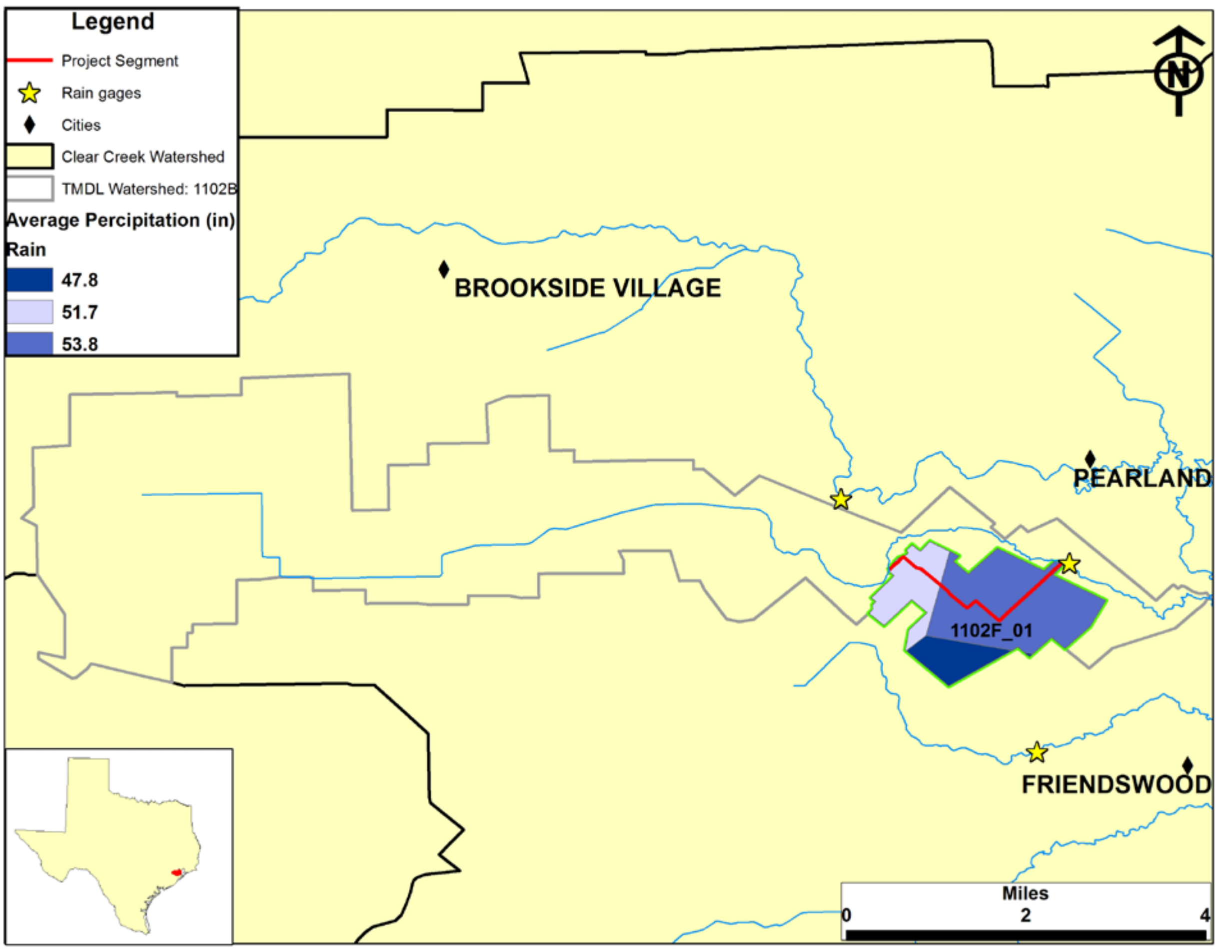

Figure 1-4: Calculated Average Precipitation for Mary's Creek Bypass

Table 1-6: Annual Totals (inches) at HCOEM Rainfall Gages near Mary's Creek Bypass Watershed

Gage number	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average
Gage 105	37.2	63.2	70.8	53.5	52.2	69.7	21.3	54.2	47.2	41.6	80.6	53.8
Gage 115	26.8	62.1	69.1	50.7	35.6	50.5	25.8	50.1	44.0	39.7	71.2	47.8
Gage 150	33.8	70.0	83.1	42.0	45.5	53.9	26.3	55.2	43.4	43.4	72.1	51.7
Average rainfall across watershed (inches)												**51.1**

Table 1-7: Average Annual HCOEM Precipitation for Mary's Creek Bypass: 2005-2015

Segment Name	Assessment Unit	Average Annual (Inches)
Mary's Creek Bypass	1102F_01	52.5

1.2.4 Ambient Water Quality

Ambient water quality data are available to support water quality assessment and development of TMDLs for segments in the Clear Creek Watershed. Historical indicator bacteria data for the period 2005 to 2012 were obtained from the TCEQ Surface Water Quality Monitoring Information System (SWQMIS) database. The data correspond to *E. coli* samples (20 samples)

Table 1-8 summarizes the historical ambient water quality data for indicator bacteria (2006-2007) for the select TCEQ Water Quality Monitoring (WQM) station in the Mary's Creek Bypass Watershed. Figure 2-1 shows the location of the WQM station with indicator bacteria data. The complete ambient water quality data set for bacteria used to prepare Table 1-8 is provided in Appendix A. Table 1-8 presents the number of indicator bacteria samples, as well as the geometric mean of the concentrations for each indicator, and the number and percentage of single sample exceedances of the Texas SWQS. A more in-depth discussion of the analysis of this data set is provided in Subsections 2.3 and 2.4.

Table 1-8: Historical Water Quality Data for TCEQ Stations from 2006 to 2007

Assessment Unit	Station ID	Indicator Bacteria	Geometric Mean Concentration (MPN/100ml)	Number of Samples	Number of Samples Exceeding Single Sample Criterion	% of Samples Exceeding
1102F_01	17917	EC	159.39	10	1	10.00%
	18639	EC		10	1	10.00%

EC: E. coli
Geometric Mean Criteria: 126 MPN/100ml for EC
Single Sample Criteria: 399 MPN/100ml for EC

1.2.5 Stream Flow Data

Stream flow data is key information when conducting water quality assessments such as TMDLs. The U.S. Geological Survey (USGS) does not maintain any current flow gages in the Study Area. To address this deficiency, flow projections were developed for the Study Area using long-term flow records from USGS gage stations outside the Study Area, but near the Clear Creek watershed. The flow projection methodology is described in detail in Chapter 4.

1.3 Mary's Creek Bypass 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 1-9) were used to divide the data sets into warmer (25 – 29°C) and cooler months (12 – 21°C). Based on these temperature ranges, November, December, January, February, and March were considered the cooler months; May, June, July, August, and September were warmer months.

Table 1-9: Average Monthly Temperatures for Houston Hobby AP, TX (1981-2010)

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

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

To determine if there was a statistically significant difference between cool and warm months, a two-tailed *t*-test can be conducted on log transformed data between the warmer months and cooler months for WQM stations with six or more bacteria samples. Geometric means can also be calculated for the warmer and cooler months. There are no stations in the Study Area with sufficient data to perform a statistically sound *t*-test. Previous analysis in the Clear Creek Watershed published in 2012 concluded that there was no difference in *E coli* concentration between the warmer and colder months (TCEQ, 2008).

CHAPTER 2

PROBLEM IDENTIFICATION AND WATER QUALITY TARGET

2.1 Pollutant of Concern: Characteristics of Bacterial Indicators

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

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

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

2.2 TCEQ Water Quality Standards for Contact Recreation

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

This report focuses on the Mary's Creek Bypass Watershed that is on the federal Clean Water Act §303(d) list because it does not support contact recreation use. Table 2-1 lists the assessment unit within Clear Creek that is on the 2014-303(d) list and provides a description of the assessment unit. Table 2-1 also identifies the year the waterbody was placed on the Texas' Clean Water Act §303(d) List for nonsupport of contact recreation use. Table 2-2 summarizes the designated uses and the applicable bacteria indicators used to assess the contact recreation use of each waterbody addressed in this report. Table 2-2 also provides the stream length in miles, and other designated uses for the waterbody. The TMDLs in this report only address the contact recreation use.

Table 2-1: Synopsis of Texas 2014 303(d) List

Assessment Unit	Segment Name	Description	Category	Year First Listed
1102F_01	Mary's Creek Bypass	From the Mary's Creek confluence NE of FM 518 to a point 0.96 km (0.60 mi) upstream to the Mary's Creek confluence (NW of County Road 126)	5a	2014

Table 2-2: Synopsis of Texas Integrated Report for the Mary's Creek Bypass

Assessment Unit	Segment Name	Parameter	Designated Use*				Year Impaired	Stream Length (miles)
			CR	AL	GU	FC		
1102F_01	Mary's Creek Bypass	*E. coli*	NS	FS	CS	NA	2014	2.37

** CR: Contact recreation; AL: Aquatic Life; GU: General Use; FC: Fish Consumption,*
NS = Not Supporting; FS = Fully Supporting; CS= Screening Level Concern; NA= Not Assessed

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

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 2-1 identifies Mary's Creek Bypass requiring a TMDL through identification as Category 5a of the 2014 Texas Water Quality Inventory and §303(d) List (TCEQ 2014). Table 2-3 lists the TCEQ SWQM station from which ambient water quality data were summarized to support the decision to place Mary's Creek Bypass on the TCEQ 303(d) List. The location of the SWQM station is displayed in Figure 2-1.

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

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

As a result of these evolving factors in the water quality management arena associated with the protection and maintenance of contact recreation use, the historical data set used to support the TMDL in this report have been narrowed, wherever possible, to utilize only *E coli* and data from 2007 through 2012. In the case of Mary's Creek Bypass, indicator bacteria data is only available between 2005 and 2007. Monitoring stations for Mary's Creek Bypass are depicted in Figure 2-1.

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

Assessment Unit	Water Body	Description	Monitoring Station IDs	Year
1102F_01	Mary's Creek Bypass	From the Mary's Creek confluence NE of FM 518 to a point 0.96 km (0.60 mi) upstream to the Mary's Creek confluence (NW of County Road 126)	17917; 18639	2014

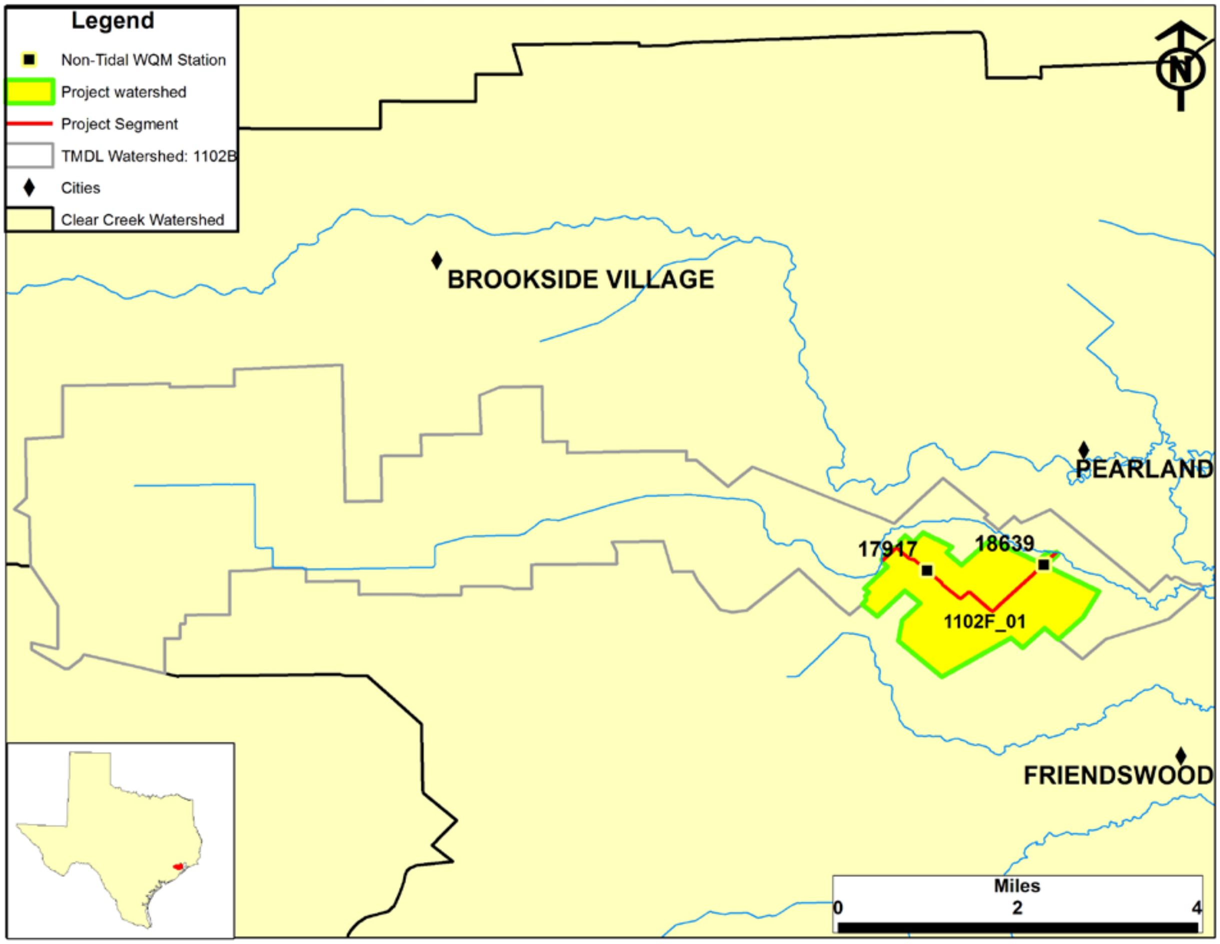

Figure 2-1: TCEQ SWQM Station in the Mary's Creek Bypass Watershed

2.4 Water Quality Targets for Contact Recreation

The Code of Federal Regulations (40 CFR §130.7(c)(1)) states that, "TMDLs shall be established at levels necessary to attain and maintain the applicable narrative and numerical water quality standards." The Texas SWQSs (TCEQ 2014) 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 2014 Texas SWQSs as described in Subsection 2.2 above. *E coli* is the preferred indicator bacteria for assessing contact recreation use in freshwater.

Several studies have been performed by the USEPA that show a stronger link between the concentrations of *E coli* and enterococci and the concentrations of fecal pathogens than the previous standard, fecal coliform. The USEPA studies found that in freshwater streams, *E coli* concentrations were the strongest predictor of illness following contact recreation. The TCEQ adopted the limit of 399 per dL for single samples of *E coli* and a geometric mean limit of 126 per dL for waterbodies that have been designated for contact recreation use. Within tidal streams and saltwater bodies, however, the USEPA determined that enterococci concentrations were the strongest predictor of illness. The TCEQ adopted a limit of 104 per dL for enterococci in any single sample, and a limit of 35 per dL for the geomean of all samples at any location for enterococci concentrations within a tidal stream designated for contact recreation uses (TCEQ 2014).

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

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

For non-tidal segments, each water quality target is used to determine the allowable bacteria load that is derived by using the actual or estimated flow record multiplied by the instream criteria minus a 5 percent MOS.

CHAPTER 3
POLLUTANT SOURCE ASSESSMENT

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

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

3.1 Point Sources: NPDES/TPDES-Permitted Sources

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

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

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

The Study Area (1102F_01) has zero NPDES/TPDES-permitted wastewater discharge sources. A significant portion of the Study Area is regulated under the TPDES stormwater discharge permit jointly held by Harris County, HCFCD, City of Houston, and Texas Department of Transportation. There are no NPDES-permitted CAFOs within the Study Area.

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

There are no TPDES-permitted WWTF facilities discharging into the Study Area. The residents in the Study Area are serviced by three WWTFs: Brazoria County MUD #18, Gulf Coast Waste Disposal Authority, and the City of Pearland WWTF, which discharge into Clear Creek.

It is important to note that these facilities provide wastewater service within Mary's Creek Bypass watershed but the facilities themselves do not discharge into Mary's Creek Bypass. The WWTF service area boundaries are shown in Figure 3-2.

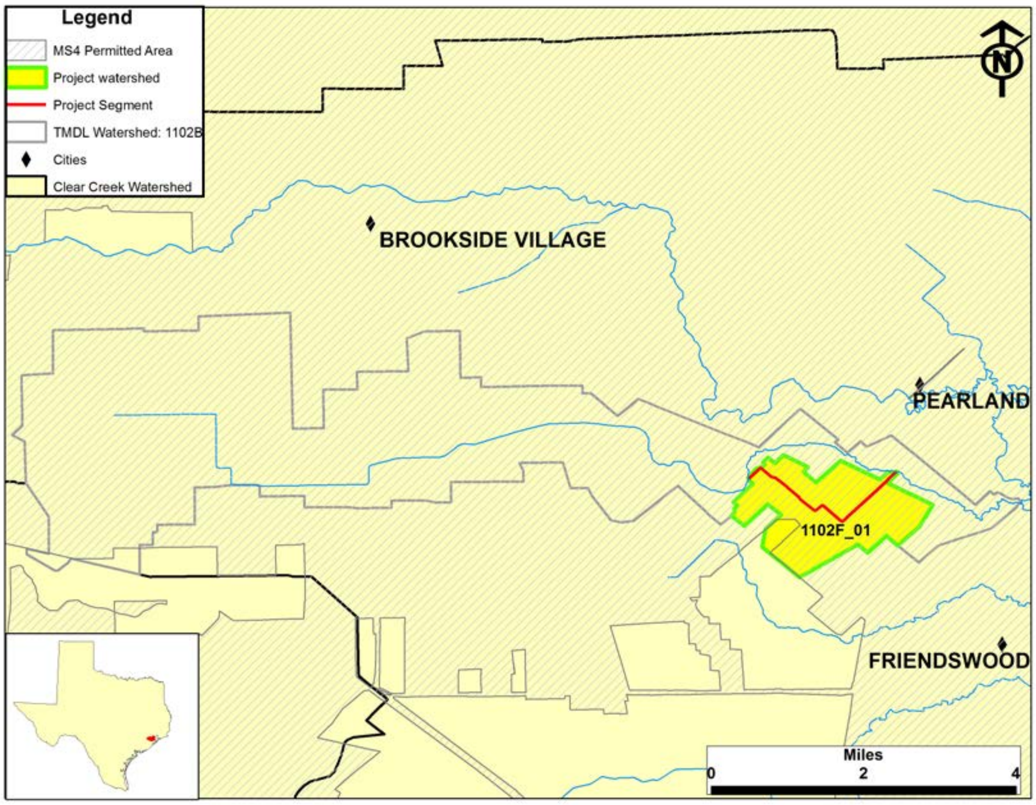

Figure 3-1: No TPDES-Permitted Facilities in the Mary's Creek Bypass Watershed

3.1.2 Permitted Sources: Sanitary Sewer Overflows

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

The TCEQ maintains a database of SSO data collected from wastewater operators in the Mary's Creek Bypass Watershed. TCEQ Region 12-Houston provided a database for SSO data in the Mary's Creek Bypass Watershed (Laird 2016). These data are included in Table 3-1.

As can be seen from Table 3-1, there have only been two sanitary sewer overflows reported in the Study Area watershed since 2001. The reported SSOs were between 300 and 22,000 gallons per event.

The locations and magnitudes of all the reported SSOs within the Study Area watershed are displayed in Figure 3-2 and summarized in Table 3-1: Sanitary Sewer Overflow (SSO) Summary.

Table 3-1: Sanitary Sewer Overflow (SSO) Summary

Facility Name	NPDES Permit No.	Facility ID	Number of Occurrences	Date Range	Amount (Gallons)
City of Pearland	TX0032743	10134-003	1	12/13/2001	22,000
Gulf Coast Waste Disposal Authority	TX0069728	11571-001	1	4/17/2008	300

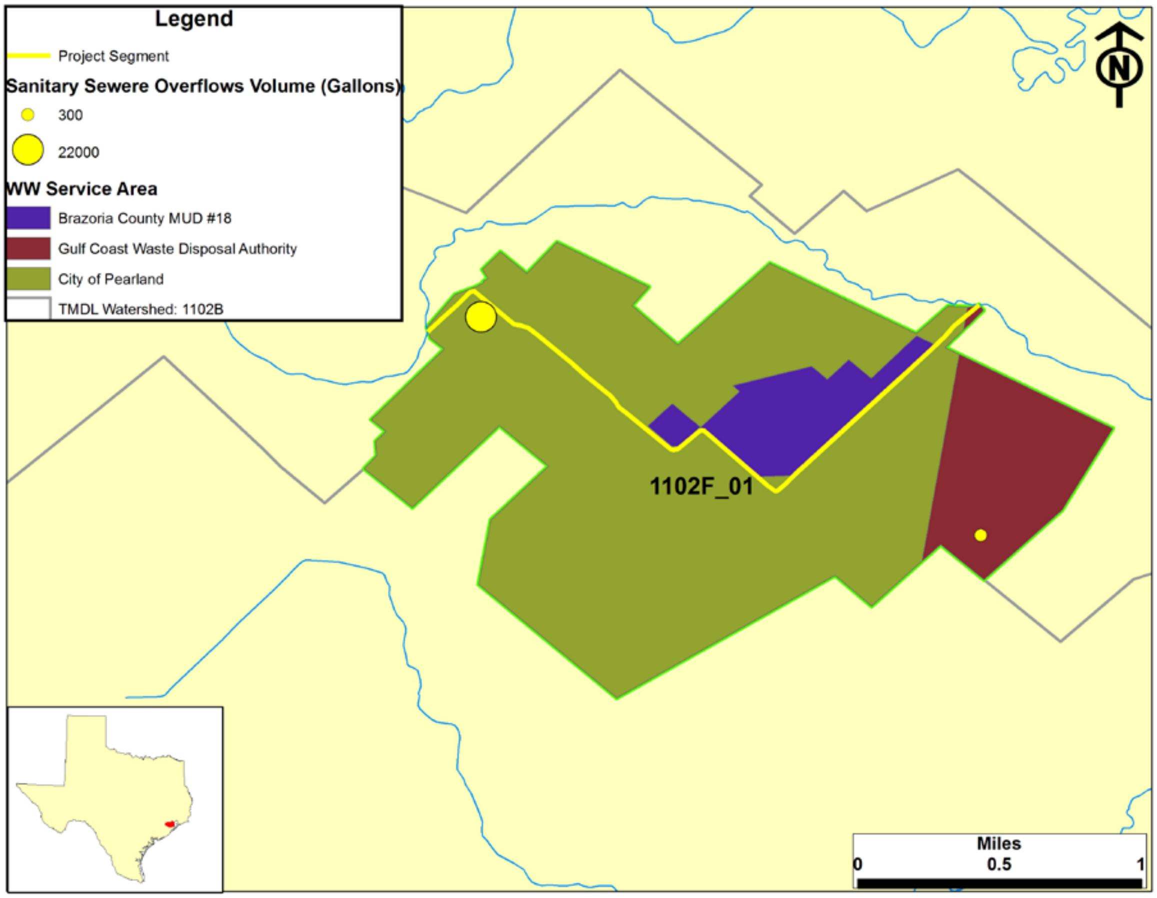

Figure 3-2: Sanitary Sewer Overflow Locations

3.1.3 Permitted Sources: TPDES Regulated Stormwater

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

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

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

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

Within the Mary's Creek Bypass watershed, there is only one individual Phase I MS4 program that is currently permitted by TCEQ. This program is operated by:

- City of Houston/Harris County (Phase I permit)

The Study Area is almost completely 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 2010 U.S. Census and can be found at the USEPA website http://cfpub.epa.gov/npdes/stormwater/urbanmapresult.cfm?state=TX.

Shown in Table 3-2 is a summary of the percentage of the Study Area watershed that is covered by one or more MS4 permits.

Table 3-2: Percentage of Permitted Stormwater in the Study Area

Segment	Receiving Stream	Regulated Entity Name	Permit Number	Total Area (acres)	Area under MS4 Permit (Acres)	Percent of Watershed under MS4 Jurisdiction
1102F_01	Mary's Creek Bypass	City of Houston/ Harris County	WQ0004685000	1309.6	1241.3	95%
		City of Pearland MS4	TXR040208			

3.1.4 Concentrated Animal Feeding Operations

There are no CAFOs located within the Study Area.

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

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

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

3.2.1 Wildlife and Unmanaged Animal Contributions

E coli and enterococci bacteria are common inhabitants of the intestines of all warm-blooded animals, including wildlife such as mammals and birds. In developing bacteria TMDLs, it is important to identify the potential for bacteria contributions from wildlife by watershed. Wildlife can be naturally attracted to riparian corridors of streams and rivers. With direct access to the stream channel, the direct deposition of wildlife waste can be a concentrated source of bacteria loading to a waterbody. In addition, *E coli* and enterococci bacteria from wildlife are also deposited onto land surfaces, where they may be washed into nearby streams by rainfall runoff.

The Study Area is fairly developed, thereby not likely to provide a favorable habitat for species of mammals, reptiles, and amphibians.

There are currently insufficient data available to estimate populations and spatial distribution of wildlife and avian species by watershed. Consequently, it is difficult to assess the magnitude of bacteria contributions from wildlife species as a general category. In general, due to the fact that urbanized areas surround the Study Area, it is unlikely that there exist large quantities of wild animals that could contribute a significant source of bacteria to Mary's Creek Bypass.

3.2.2 Unregulated Agricultural Activities and Domesticated Animals

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

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

The estimated numbers of selected livestock by watershed were calculated based on the 2012 USDA county agricultural census data (USDA 2012). The county-level estimated livestock populations were distributed among watersheds based on GIS calculations of pasture land per watershed, based on the National Land Cover Database (NOAA 2011). It should be noted that these are planning level livestock populations which are not evenly distributed across counties or constant with time. As shown in Table 3-3, cattle are estimated to be the most abundant species of livestock in the Study Area.

Table 3-3: Livestock and Manure Estimates by Watershed

Type of Animal	Total Animals
Cattle and Calves	2
Horses and Ponies	0
Goats	0
Hogs and Pigs	0
Sheep and Lambs	0
Bison	0
Captive Deer	0
Donkey	0
Rabbits	0
Llamas	0
Pullets	0
Broilers	0
Layers	0
Turkeys	0
Ducks	0
Geese	0
Other Poultry	0
Total Animals	2

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

- Beef cattle release approximately 1.04E+11 per animal per day
- Dairy cattle release approximately 1.01E+11 per animal per day

Using the estimated livestock populations and the fecal coliform production rates from ASAE, an estimate of fecal coliform production from each group of livestock was calculated in Table 3-4 for each watershed of the Study Area. It should be noted that only a fraction of these fecal coliform loading estimates is expected to reach the receiving water, either washed into streams by runoff or by direct deposition from wading animals. Cattle appear to represent the most significant livestock source of fecal bacteria based on overall loading estimates.

Table 3-4: Fecal Coliform Production Estimates for Selected Livestock (x10^9 /day)

Stream Name	**Cattle & Calves** Fecal Coliform (x10^9 /day)	**Total** Fecal Coliform (x10^9 /day)
Mary's Creek Bypass	205	205

3.2.3 Failing On-site Sewage Facilities

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

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

Only permitted OSSF systems are recorded by authorized county or city agents; therefore, it is difficult to estimate the exact number of OSSFs in use in the Study Area. Figure 3-3 displays the locations of OSSFs within the study area. Table 3-5 lists the OSSF totals based on GIS data information provided by H-GAC. There are currently no areas without sewer service in the Study Area which may be expected to have septic systems.

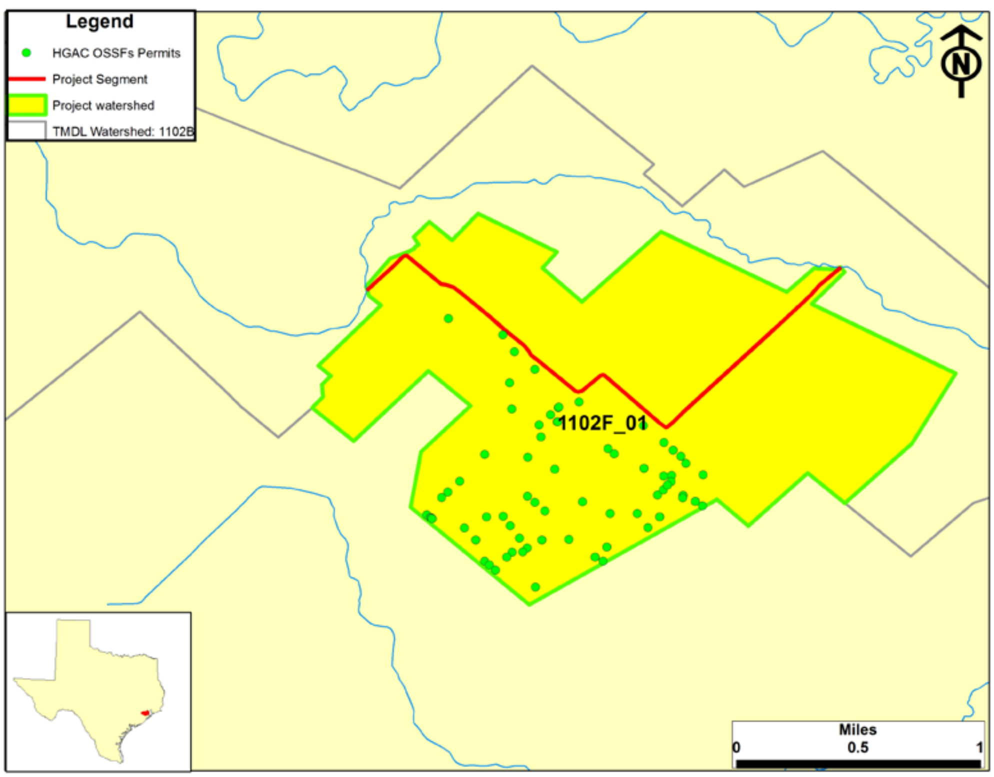

Figure 3-3: OSSFs in the Study Area

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

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

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

The average of number of people per household was calculated to be 2.75 for the Study Area (U.S. Census Bureau 2010) based on an average household density for Houston, and Jersey Village. Approximately 70 gallons of wastewater were estimated to be produced on average per person per day (Metcalf and Eddy 1991). The fecal coliform concentration in failing septic tank effluent was estimated to be 10^6 per 100 mL of effluent based on reported concentrations from a number of published reports (Metcalf and Eddy 1991; Canter and Knox 1985; Cogger and Carlile 1984). Using this information, the estimated load from failing septic systems within each subwatershed was calculated and is summarized in Table 3-5. Based on this data, it was determined that the estimated fecal coliform loading from OSSFs in the Study Area were found to be negligible.

Table 3-5: Estimated Number of OSSFs per Watershed and Fecal Coliform Load

Segment	Stream Name	OSSF data from H-GAC	# of Failing OSSFs	Estimated Loads from OSSFs (x 10^9 counts/day)
1102F_01	Mary's Creek Bypass	82	9.84	71.70

3.2.4 Domestic Pets

Fecal matter from dogs and cats is transported to streams by runoff from urban and suburban areas and can be a potential source of bacteria loading. On average nationally, there are 0.58 dogs per household and 0.66 cats per household (American Veterinary Medical Association 2002). Using the U.S. Census data at the block level (U.S. Census Bureau 2010), dog and cat populations can be estimated for each watershed. Table 3-6 summarizes the estimated number of dogs and cats for the watersheds of the Study Area.

Table 3-6: Estimated Numbers of Pets

Segment	Stream Name	Dogs	Cats
1102F_01	Mary's Creek Bypass	1411	1606

Table 3-7 provides an estimate of the fecal coliform load from pets. These estimates are based on estimated fecal coliform production rates of $5.4x10^8$ per day for cats and $3.3x10^9$ per day for dogs (Schueler 2000). Only a small portion of these loads are expected to reach waterbodies, through wash-off of land surfaces and conveyance in runoff.

Table 3-7: Fecal Coliform Daily Production by Pets (x 10^9)

Segment	Stream Name	Dogs	Cats	Total Load (cfu/day x 10^9)
1102F_01	Mary's Creek Bypass	4656	867	5523

3.2.5 Bacteria Re-growth and Die-off

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

CHAPTER 4
TECHNICAL APPROACH AND METHODS

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

TMDL = Σ WLA + Σ LA + MOS

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

40 CFR §130.2(1), states that TMDLs can be expressed in terms of mass per time, toxicity, or other appropriate measures. For *E coli* or enterococci bacteria, TMDLs are expressed as numbers per day, where possible, or as a percent reduction goal, and represent the maximum one day load the stream can assimilate while still attaining the standard for contact recreation. For the Mary's Creek Bypass Watershed, to quantify allowable pollutant loads, percent reduction goals to achieve standard for contact recreation and specific TMDL allocations for point and nonpoint sources, the load duration curve method for non-tidal streams is used. The technical approach is 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 FDCs and LDCs, which facilitate development of TMDLs. As a TMDL development tool, they can be effective at identifying whether impairments are associated with point or nonpoint sources. The technical approach for using FDCs and LDCs for TMDL development includes the four following steps described in Subsections 4.2 through 4.4 below:

1. Preparing flow duration curves (FDC) for gaged and ungaged WQM stations;
2. Using the FDCs to identify the critical conditions that will be used to calculate the TMDL;
3. Calculate the LDCs from the FDCs.
4. Using the LDCs to estimate existing ambient bacteria loading in the receiving water and derive TMDL elements – WLA, LA, MOS;
5. Using these TMDL elements and ambient loading to estimate percent reduction goals necessary to attain the contact recreation standard.

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

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

4.2 Development of Flow Duration Curves

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

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

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

While the number of observations required to develop a flow duration curve is not rigorously specified, a flow duration curve is usually based on more than 5-years of observations, and encompasses inter-annual and seasonal variation. Ideally, the drought of record and flood of record are included in the observations. For this purpose, the long-term flow gaging stations operated by the USGS are utilized. As previously mentioned, there are no long-term flow data from within the Study Area and therefore, flows were estimated for all WQM stations/watersheds in Mary's Creek Bypass using the gage correlation approach described in Appendix C. Two USGS gages outside the Study Area, Sims Bayou at Hiram Clarke, Houston, TX (USGS gage number: 08075400), and

Vince Bayou at Pasadena, TX (USGS gage number: 08075730), were chosen to conduct flow projections. The period of record for flow data used from these stations was 2005 through 2015.

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

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

Table 4-1: Hydrologic Classification Scheme

Flow Exceedance Percentile	Hydrologic Condition Class
0-30	Wet conditions
30-70	Intermediate flows
70-100	Dry conditions

Figure 4-1 presents the FDC developed for the WQM station in Mary's Creek Bypass for calculating the TMDL of the 303(d)-listed freshwater stream using the gage correlation method outlined above and further described in Appendix C. The flow exceedance percentiles for these segments are presented in tabular form in Appendix B.

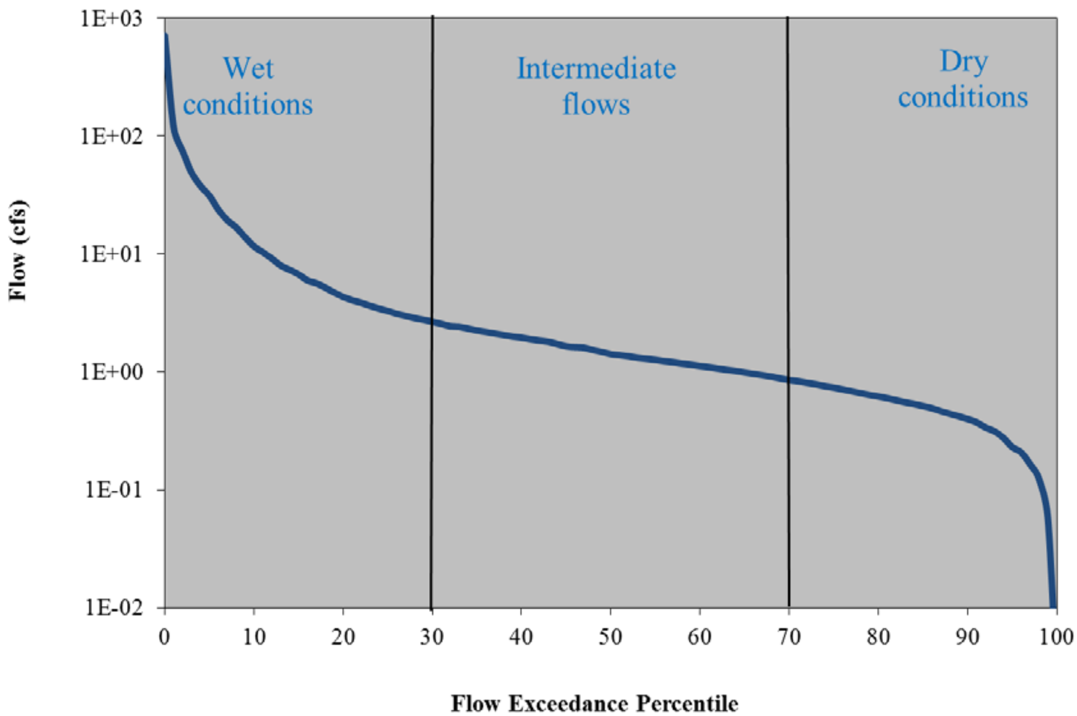

Figure 4-1: Flow Duration Curve for Mary's Creek Bypass (1102F_01)

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

Another key step in the use of LDCs for TMDL development is the estimation of existing bacteria loading from point and nonpoint sources and the display of this loading in relation to the TMDL. There were domestic or otherwise continuously discharging point sources (i.e., WWTFs) in the watershed. Therefore, the TMDL was allocated between stormwater waste load allocation, WWTF waste load allocation and the load allocation based on the percentage of the watershed covered by MS4 permits.

The critical condition for the load duration curve is considered the flow regime that requires the most significant bacteria reduction to meet water quality standards. For the watershed of interest, this was the high flow (0-30th percentile flow) condition.

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

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

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

- Developing flow estimates using the gage correlation approach described in Appendix C and developing flow duration curve as described in previous sections;
- Obtaining the water quality data for the WQM station;
- Matching the water quality observations with the flow estimates from the same date;
- Displaying a curve on a plot that represents the allowable load multiply the actual or estimated flow by the surface water quality standard for each respective indicator;
- Multiplying the flow by the water quality parameter concentration to calculate daily loads; then
- Plotting the flow exceedance percentiles and the daily observed bacteria load.

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

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

Where: criterion = 126 counts/dL (E coli) and

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

The flow exceedance frequency (x-value of each point) is obtained by looking up the historical exceedance frequency of the measured or estimated flow; in other words, the percent of historical observations that equal or exceed the measured or estimated flow. Historical observations of bacteria concentration are paired with flow data and are plotted on the LDC. The indicator bacteria load (or the y-value of each point) is calculated by multiplying the indicator bacteria concentration (counts/dL) by the instantaneous flow (cubic feet per second [cfs]) at the same site and time, with appropriate volumetric and time unit conversions. Indicator bacteria loads representing exceedance of water quality criterion fall above the water quality criterion line.

Figure 4-2 provides a schematic representation of where permitted and unregulated sources of pollution occur throughout the entire hydrograph for a typical stream. This figure shows that runoff typically contributes pollutant loads during high flow to mid-ranged flow conditions. However, flows do not always correspond directly to runoff events. For instance, high flows may occur in dry weather and runoff influence may be observed with low or moderate flows.

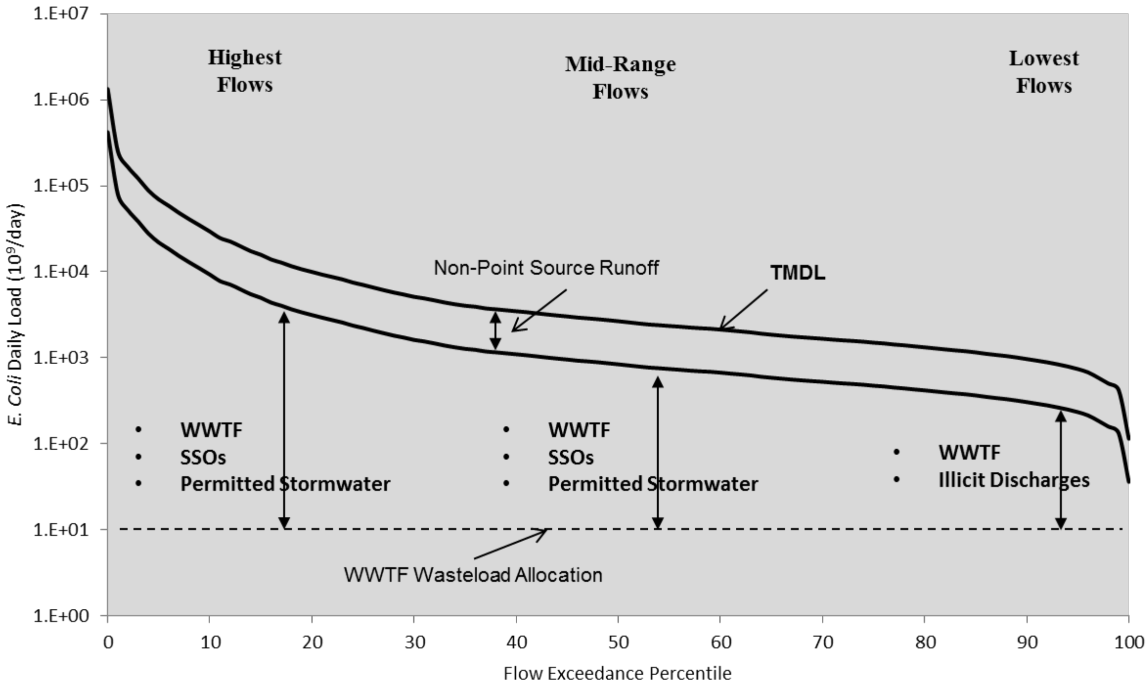

Figure 4-2: Schematic Diagram – Interpreting Sources and Loads

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

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

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

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

WLA for NPDES/TPDES MS4s. Given the lack of data and the complexity of quantifying bacteria concentrations or loads associated with wet weather events, the percentage of a watershed that is under MS4 jurisdiction is used to estimate the load that should be allocated as the permitted stormwater load. For example, the area of the City of Houston/Harris County permitted MS4 discharges in the project area is estimated to be 1310 acres, 95 percent of the Mary's Creek Bypass (Segment 1102F_01) watershed. Therefore, 95 percent of the wasteload allocation will be designated as the WLA for stormwater.

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

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

Where:

LA = allowable load from unregulated sources

TMDL= total allowable load

ΣWLA_{WWTF} = sum of all WWTF loads

ΣWLA_{MS4} = sum of all MS4 loads

MOS = margin of safety

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

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

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

CHAPTER 5
TMDL CALCULATIONS

5.1 Results of TMDL Calculations

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

5.2 Estimated Loading and Critical Conditions

USEPA regulations at 40 CFR 130.7(c) (1) require TMDLs to take into account critical conditions for stream flow, loading, and all applicable water quality standards. To accomplish this, available in-stream WQM data were evaluated with respect to stream flows, and the magnitude of water quality criteria exceedance. TMDLs are derived for specific indicator bacteria in 303(d) listed water bodies at specific WQM stations based on LDCs for Mary's Creek Bypass (1102F_01) and a mass balance calculation using a tidal prism for tidal streams.

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

The pollutant load allocations and percent reduction goals for each flow regime are summarized in Section 5.8. The highest percent reduction goals for the segment were found to occur in the wet flow conditions regime (0–30th percentile) and consequently, this was the flow regime used to estimate the TMDL.

Figure 5-1 represents the LDC for Mary's Creek Bypass (1102F_01) based on *E coli* bacteria measurements at sampling locations 17917 (Mary's Creek Bypass at Dixie Farm) and 18639 (Mary's Creek Bypass at FM 518). The LDC indicates that geometric mean observed *E coli* loading exceeds the TMDL, established using the geometric mean water quality target, under wet conditions and mid-range flows. A 62.3% reduction of the observed loads is required in order to meet the TMDL under the high flow condition.

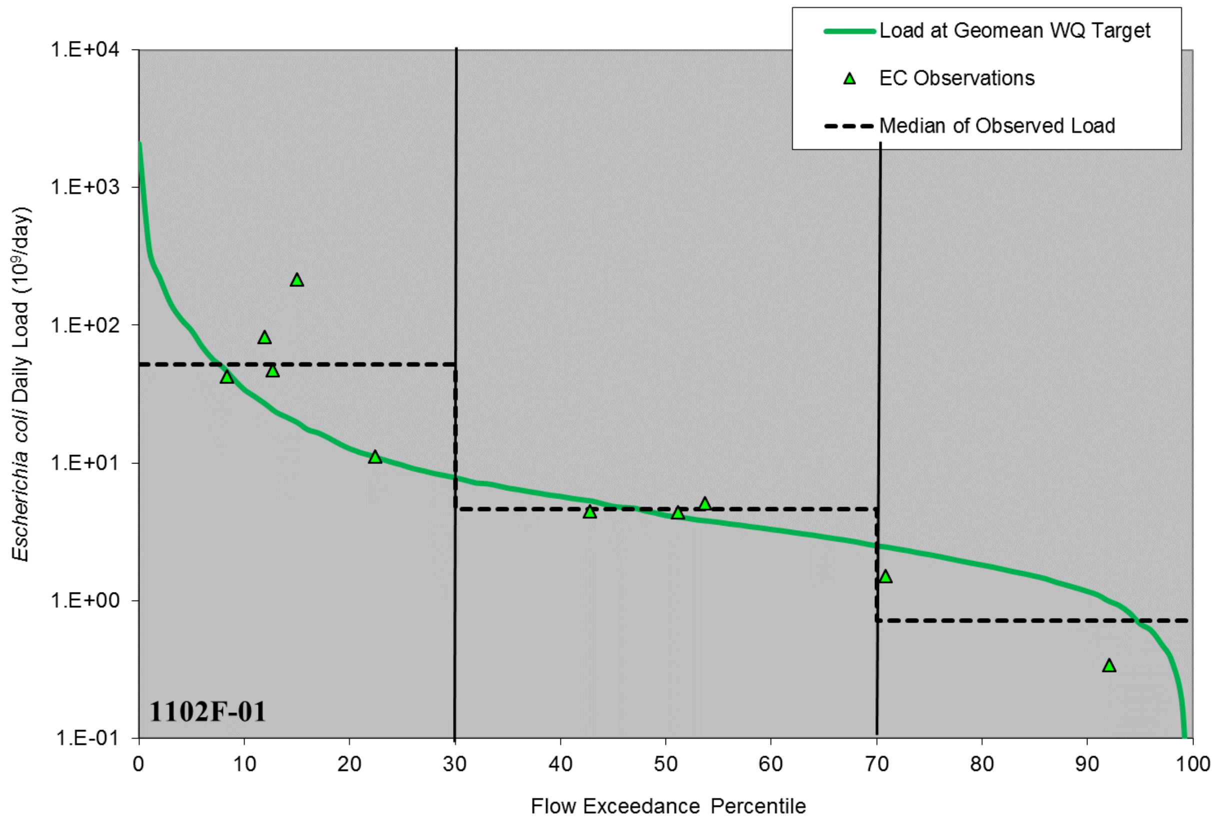

Figure 5-1: Load Duration Curve for Mary's Creek Bypass (1102F_01)

5.3 Wasteload Allocation

TPDES-permitted facilities are allocated a daily waste load calculated as their permitted discharge flow rate multiplied by one half of the in-stream geometric mean water quality criterion. 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 = 35 and 126 counts/dL for enterococci and E coli, respectively

flow (10^6 gal/day) = permitted flow

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

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

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

For the freshwater stream, the flow dependent calculations for the MS4 portion of the WLA are derived using LDC and the MS4 percentages provided in Table 3-2.

5.4 Load Allocation

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

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

Where:

LA = allowable load from unregulated sources

TMDL= total allowable load

ΣWLA_{WWTF} = sum of all WWTF loads

$\sum WLA_{STORMWATER}$ = sum of all Stormwater loads

MOS = margin of safety

5.5 Seasonal Variability

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

Though there was insufficient data in the Study Area to assess seasonal impacts, previous analysis in the Clear Creek Watershed published in 2012 concluded that there was no difference in *E coli* concentration between the warmer and colder months (TCEQ, 2012).

5.6 Allowance for Future Growth

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

To account for the high probability that new additional flows from WWTF may occur in any of the segments, a provision for future growth was included in the TMDL calculations by estimating permitted flows to year 2050 using population projections completed by the Texas Water Development Board. Because, the drainage area of Mary's Creek Bypass is entirely serviced by WWTFs whose outfall locations lie outside the watershed boundaries, no estimated future flow increase is necessary.

5.7 Margin of Safety

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

The TMDL for the freshwater segment incorporates an explicit MOS by setting a more stringent target for indicator bacteria loads that is 5 percent lower than the single sample criterion. The explicit margin of safety was used because of the limited amount of data. For contact recreation, this equates to a single sample target of 379 MPN/100mL for *E coli* and a geometric mean target of 120 MPN/100mL. The net effect of the TMDL with MOS is that the assimilative capacity or allowable pollutant loading of each waterbody is slightly reduced. The TMDL for the freshwater stream in this report incorporate an explicit MOS in the LDC by using 95 percent of the single sample criterion.

5.8 TMDL Calculations

The TMDL is computed by multiplying the geomean flow for the highest flow regime by the geomean criterion. This TMDL is then compared to observed loads using LDCs. Finally, it is allocated to various loads as follows.

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:

$$\textit{TMDL} = \Sigma\ \textit{WLA} + \Sigma\ \textit{LA} + \textit{MOS} + \textit{Future Growth}$$

Table 5-1 summarizes the pollutant load allocations and percent reduction goals at current flows, for each flow regime, for the freshwater segments. Table 5-2 summarizes the estimated maximum allowable load of *E coli* for the freshwater assessment unit in this project.

Table 5-1: *E. coli* TMDL Calculations for Mary's Creek Bypass (1102F_01)

Station 11157			
Flow Regime %	**0%-30%**	**30%-70%**	**70%-100%**
Median Flow [a], Q (cfs)	6.7276	1.4	0.5
TMDL [b] (10^9 org/day)	2.07E+01	4.37E+00	1.58E+00
MOS [c] (10^9 org/day)	1.04E+00	2.18E-01	7.92E-02
Allowable Load at Water Quality Target [d]	1.97E+01	4.15E+00	1.51E+00
Observed Geomean Load [e] (10^9 org/day)	5.22E+01	4.64E+00	7.13E-01
Load Reduction [f] (10^9 org/day)	3.25E+01	4.93E-01	0.00E+00
Load Reduction (%)	62.3%	10.6%	0.0%
TMDL (Qfuture * WQS) (10^9 org/day)	0.00E+00	*n/a*	*n/a*

[a] Geomean flow = Median flow in wet conditions, intermediate flows, and dry conditions
*[b] TMDL = Contact recreation standard (126 MPN/dL)*median flow*unit conversion factor*
*[c] MOS = TMDL*0.5*
[d] Allowable load at water quality target = TMDL - MOS
*[e] Observed geomean load = Bacteria load (MPN/dL)*flow*conversion factor*
[f] Load reduction = Observed geomean load – Allowable load a t water quality target

Table 5-2: *E. coli* TMDL Summary Calculations for Mary's Creek Bypass

Assess-ment Unit	Stream Name	Indicator Bacteria	TMDL[a] (MPN/day)	WLA_{WWTF}[b] (MPN/day)	$WLA_{STORMWATER}$[c] (MPN/day)	LA[d] (MPN/day)	MOS[e] (MPN/day)	Future Growth[f] (MPN/day)
1102F_01	Mary's Creek Bypass	*E coli*	2.07E+10	0.00E+00	1.87E+10	1.03E+09	1.04E+09	0.00E+00

[a] Maximum allowable load for the flow range requiring the highest percent reduction (Table 5-2)
*[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*
[c] $WLA_{STORMWATER}$ = (TMDL – MOS –WLA_{WWTF})(percent of drainage area covered by stormwater permits)*
[d] LA = TMDL – MOS –WLA_{WWTF} –$WLA_{STORMWATER}$-Future growth
[e] MOS = TMDL x 0.05
*[f] Projected increase in WWTF permitted flows*126/2*conversion factor*

CHAPTER 6
PUBLIC PARTICIPATION

To provide focused stakeholder involvement in the Mary's Creek Bypass Bacteria TMDL and the implementation phase, a 24-member steering committee was formed. In accordance with House Bill 2912, the group has balanced representation within the watershed and commitment was formalized. TCEQ approved the formation of a Clear Creek stakeholder group and approved the membership.

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

CHAPTER 7
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APPENDIX A
AMBIENT WATER QUALITY BACTERIA DATA – 2005 TO 2012

Table A-1: Ambient water quality *E. coli* data at the monitoring station

Segment	Station ID	Description	Single Sample Criterion	Value	Sample Exceeding	Geo-metric Mean (MPN/ 100ml)	Number of Samples	Number of Samples Exceeding Criteria	% of Samples Exceeding	Sampling Date
1102F	17917	EC	399	41						1/25/06
1102F	17917	EC	399	160						4/5/06
1102F	17917	EC	399	98						5/17/06
1102F	17917	EC	399	120						7/24/06
1102F	17917	EC	399	120						9/20/06
1102F	17917	EC	399	1300	1300					11/28/06
1102F	17917	EC	399	120						2/7/07
1102F	17917	EC	399	360						3/28/07
1102F	17917	EC	399	230						5/31/07
1102F	17917	EC	399	110						8/22/07
1102F	18639	EC	399	130						1/25/06
1102F	18639	EC	399	20						4/5/06
1102F	18639	EC	399	41						5/17/06
1102F	18639	EC	399	310						7/24/06
1102F	18639	EC	399	73						9/20/06
1102F	18639	EC	399	290						11/28/06
1102F	18639	EC	399	100						2/7/07
1102F	18639	EC	399	390						3/28/07
1102F	18639	EC	399	260						5/31/07
1102F	18639	EC	399	1200	1200	159.36	20	2	10%	8/22/2007

APPENDIX B
USGS FLOW DATA

Table B-1: Flow exceedance percentile at the USGS gages

GAGE NO.	08075400	08075730
Name	Sims Bayou at Hiram Clarke, Houston, TX	Vince Bayou at Pasadena, TX
Percentile		
0	3175.369	1700.00
1	528.6528	273.88
2	333.0449	192.00
3	218.7929	131.52
4	169.0522	98.36
5	139.1805	82.20
6	106.3983	64.00
7	86.35215	50.00
8	75.11916	41.00
9	61.78629	33.00
10	51.87398	28.00
11	46.18211	24.00
12	40.82605	21.00
13	35.6704	18.00
14	32.78883	16.00
15	30.03036	14.00
16	26.62662	12.00
17	25.20625	11.00
18	23.16203	10.00
19	21.02397	9.20
20	19.33152	8.48
21	18.10767	7.90
22	17.25338	7.30
23	16.24629	6.70
24	15.40924	6.42
25	14.68879	6.10
26	13.89228	5.70
27	13.34708	5.40
28	12.77385	5.10
29	12.35094	4.90
30	11.89921	4.70

31	11.41474	4.40
32	10.89921	4.30
33	10.78022	4.10
34	10.42202	4.00
35	10.01752	3.80
36	9.742234	3.70
37	9.44266	3.60
38	9.180514	3.49
39	8.891952	3.40
40	8.712306	3.30
41	8.442217	3.20
42	8.236491	3.10
43	8.050991	3.00
44	7.694238	2.90
45	7.368223	2.80
46	7.236491	2.70
47	7.165268	2.60
48	6.845213	2.50
49	6.600268	2.50
50	6.323974	2.40
51	6.18931	2.30
52	6.048153	2.30
53	5.874781	2.20
54	5.768842	2.10
55	5.649853	2.10
56	5.500896	2.00
57	5.395255	2.00
58	5.24919	1.90
59	5.142892	1.90
60	5.009063	1.80
61	4.90379	1.80
62	4.774745	1.70
63	4.653975	1.70
64	4.55303	1.70
65	4.418071	1.60
66	4.302875	1.60
67	4.19235	1.60
68	4.074859	1.50
69	3.925811	1.50
70	3.807164	1.40
71	3.723974	1.40

72	3.607164	1.40
73	3.507164	1.30
74	3.381377	1.30
75	3.28931	1.30
76	3.174697	1.20
77	3.060612	1.20
78	2.951894	1.20
79	2.85159	1.10
80	2.76211	1.10
81	2.672436	1.10
82	2.567356	1.00
83	2.468309	0.99
84	2.386958	0.96
85	2.294657	0.92
86	2.201707	0.90
87	2.072504	0.87
88	1.974053	0.84
89	1.876528	0.80
90	1.776776	0.76
91	1.670978	0.72
92	1.512123	0.68
93	1.404587	0.63
94	1.236353	0.59
95	1.031772	0.54
96	0.93	0.50
97	0.738686	0.46
98	0.554475	0.40
99	0.258173	0.30
100	0.01	0.07

*Data from 1/1/2005 - 12/31/2015 was used to create Flow Exceedance Percentile

APPENDIX C

GENERAL METHODS FOR ESTIMATING FLOW AT SWQM STATIONS

Because there are no USGS or HCFCD flow gages located in the Mary's Creek Bypass Subwatershed, a procedure was developed for estimating historical flows at multiple locations in the area. There were two gages available nearby with more than ten years of daily flow data. To support LDC development, ten years of daily flow estimates are needed at the impaired location in the Bayou.

Approach

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

Data

Extended periods of daily flow records are available on Sims Bayou at Hiram Clarke, Houston, TX (USGS gage number: 08075400), and Vince Bayou at Pasadena, TX (USGS gage number: 08075730). They are adjacent to the Study Area and similar in land use. A comparison of the two gages is provided in Table C-1. In addition, a summary of land cover for each of the gage drainage areas is presented in Table C-2 and compared with the land cover for the Study Area. In addition, a graphical comparison of land cover and gage locations is shown in Figure C-1.

Table C-1: USGS Gages in the area with a Continuous Period of Record from 2005-2015

Gage Number	Name	Percent		Drainage Area (acres)	Mean Flow (cfs)	Number of Continuous Data Points
		Developed Land	Forest/Wetland			
08075400	Sims Bayou at Hiram Clarke, Houston, TX	77.7%	7.2%	13279	33.3	4017
08075730	Vince Bayou at Pasadena, TX	98.2%	0.9%	4863	17.1	4017

Table C-2: Land Cover Summary

	1102F_01		Gage 08075730 Drainage		Gage 08075400 Drainage	
Land cover class	Acres	%	Acres	%	Acres	%
Open Water	4.0	0.31%	12	0%	116	1%
Developed, Open Space	384.8	29.38%	679	14%	2424	18%
Developed, Low Intensity	395.7	30.21%	1125	23%	2791	21%
Developed, Medium Intensity	378.5	28.90%	2043	42%	4403	33%
Developed, High Intensity	31.4	2.40%	927	19%	698	5%
Barren Land	0.2	0.02%	2	0%	40	0%
Deciduous Forest	28.3	2.16%	41	1%	639	5%
Evergreen Forest	15.8	1.21%	0	0%	58	0%
Mixed Forest	4.0	0.31%	0	0%	42	0%
Shrub/Scrub	1.8	0.14%	7	0%	263	2%
Herbaceous	57.5	4.39%	8	0%	332	2%
Hay/Pasture	4.7	0.36%	16	0%	1250	9%
Woody Wetlands	2.9	0.22%	0	0%	222	2%
Total	1309.6	100.00 %	4863	100%	13279	100%
Total Developed	1190.4	90.90%	4775	98%	10316	78%
Total Forest/Wetland	51.0	3.90%	42	1%	962	7%

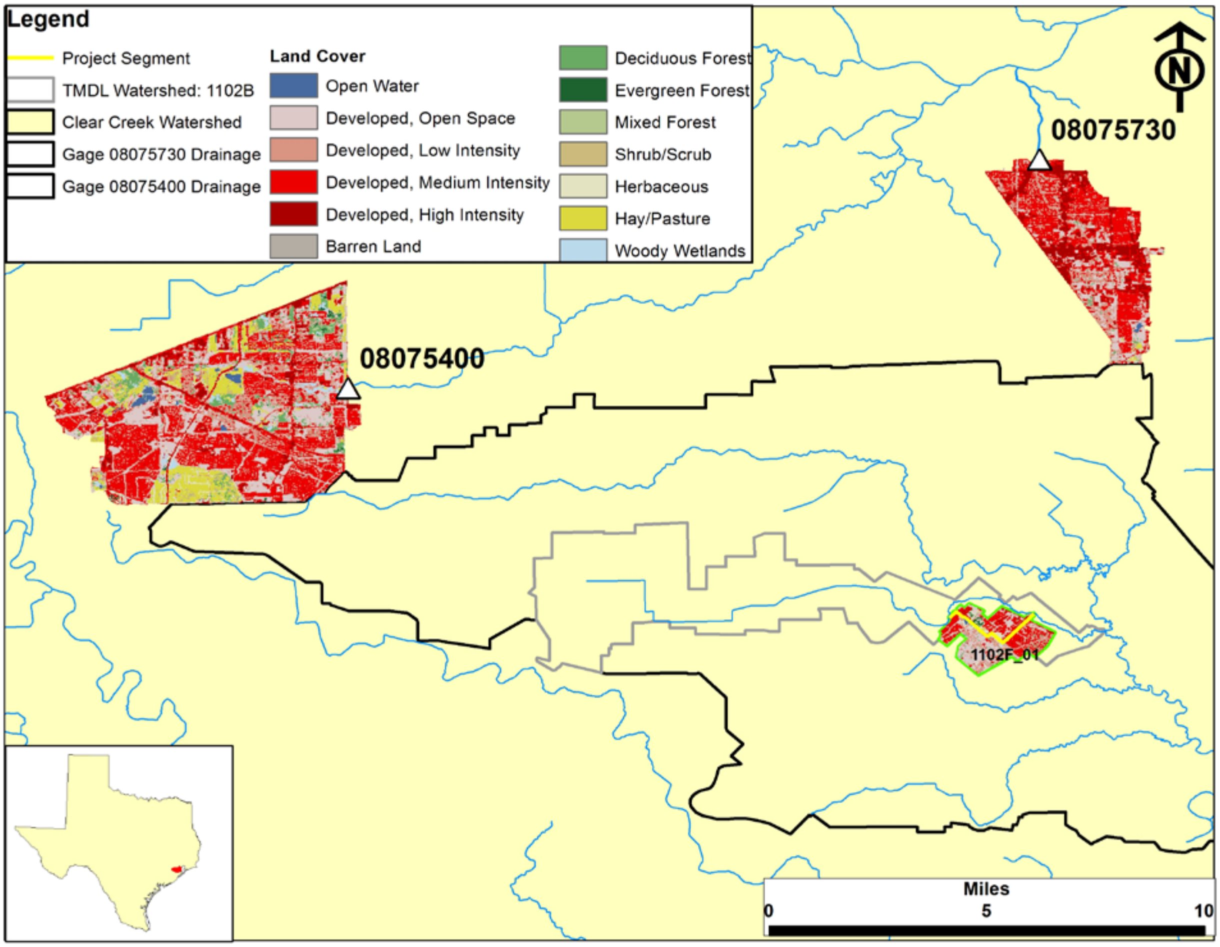

Figure C-1: USGS Gage locations

Model Development

<u>Model form</u>

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

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

Where:

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

In general, the time interval of the data is not important so long as the measurements are contemporaneous and equivalently averaged as there is no such thing as a truly instantaneous flow rate. In this case the input and output of the model are average daily flows. An analysis in log space produced significant but lower correlations thus a contemporaneous liner model was selected. Next, the model coefficients were selected based on the following model form.

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

Where:

Q_u= unknown flow

Q_k= known flow;

A= Drainage area ratio

D= Developed area ratio

W= Wetland/Forest area ratio

x, y, z = parameters

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

Parameter Selection

The model parameters were selected using the following process:

- Reasonable model parameters were selected.
- The 08075400 gage was used as input to the model, and used to compare to the known flows at 08075730.
- Through an iterative process, the model parameters were refined to improve the fit between the two gages.

A total of three wastewater treatment plants are located on the flow path of 08075400 gage and none on the flow path of 08075730. In order to properly use the USGS gage flows for the gage correlation approach, it was necessary to establish base flows without the plants. This was accomplished as follows:

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

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

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

Final Model

The final model parameters used to estimate flows in Mary's Creek Bypass watershed were as follows:

- $X = 0.324$
- $Y = 0.231$
- $Z = 0.083$

Goodness of Fit

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

To demonstrate the fit that was achieved using the above model, an example of the flow duration curve developed based on the USGS gage flow for gage 08075730 compared with the projected flows is presented in Figure C-2. As shown in the Figure, the fit over the entire range of flow conditions is quite good. The model under predicts a small amount at the very low flow conditions (i.e., less than the 10th percentile). There is also a small amount of under prediction in the high flows, with mid-range flows being slightly overestimated.

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

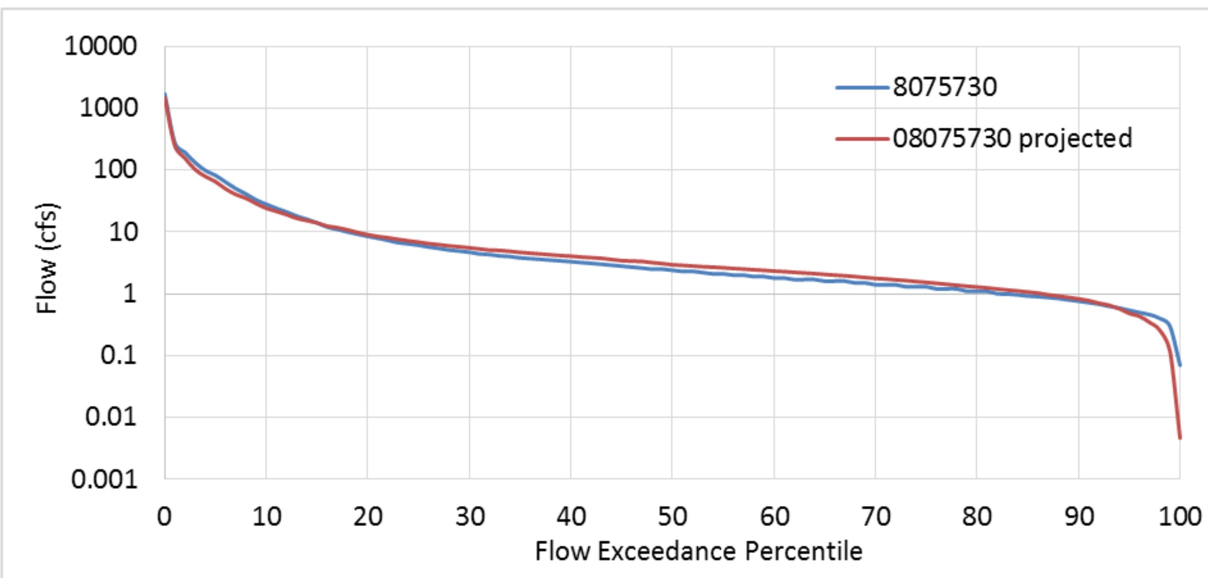

Figure C-2: Gage 08075730 Correlation Model Comparison

Table C-3: Gage Correlation Model Fit

Gage Number	Name	Mean Daily Residuals (cfs)	Root Mean Square Error (cfs)	No. Data Points
08075730	Vince Bayou at Pasadena, TX	12.53	44.72	4,017

Model application

This approach was used to develop flow duration curves for the Study Area. The flow exceedance tables developed using the gage correlation model (using USGS gages 08075400 and 08075730) are presented in Table C-4.

Table C-4: Flow Exceedance Percentiles (cfs)

Percentile	1102F_01
10	0.40
20	0.62
30	0.85
40	1.12
50	1.42
60	1.95
70	2.67
80	4.33
90	11.62
100	711.37