Technical Support Document for One Total Maximum Daily Load for Indicator Bacteria in Hillebrandt Bayou

Segment: 0704

Assessment Unit: 0704_02

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Prepared for
Total Maximum Daily Load Program
Texas Commission on Environmental Quality
MC-203
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November 2019

(revised June 2020)

Acknowledgements

The U.S. Environmental Protection Agency and the Texas Commission on Environmental Quality provided financial support for this study. The Texas Commission on Environmental Quality was the study's lead agency.

Contents

Figures

Tables

List of Abbreviations

AU	assessment unit
AVMA	American Veterinary Medical Association
CCN	Certificate of Convenience and Necessity
CFR	Code of Federal Regulations
cfs	cubic feet per second
cfu	colony forming unit
DAR	drainage-area ratio
E. coli	*Escherichia coli*
FIB	fecal indicator bacteria
FDC	flow duration curve
FG	future growth
I&I	inflow and infiltration
LA	load allocation
LDC	load duration curve
MGD	million gallons per day
mL	milliliter
MOS	margin of safety
MS4	municipal separate storm sewer system
NHD	National Hydrography Dataset
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Efficiency
OSSF	on-site sewage facility
RMSE	root mean square error
RMU	Resource Management Unit
SSO	sanitary sewer overflow
SSURGO	Soil Survey Geographic
SWMP	Stormwater Management Program
SWQM	surface water quality monitoring
SWQMIS	Surface Water Quality Monitoring Information System
TCEQ	Texas Commission on Environmental Quality
TMDL	total maximum daily load
TPDES	Texas Pollutant Discharge Elimination System
TPWD	Texas Parks and Wildlife Department
TWDB	Texas Water Development Board
TWRI	Texas Water Resources Institute
USCB	United States Census Bureau
USDA	United States Department of Agriculture

USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WLA	wasteload allocation
WLA_{SW}	wasteload allocation from regulated stormwater
WLA_{WWTF}	wasteload allocation from wastewater treatment facilities
WUG	Water User Group
WWTF	wastewater treatment facility

Section 1. Introduction

1.1. Background

Section 303(d) of the federal Clean Water Act requires all states to identify waters that do not meet, or are not expected to meet, applicable water quality standards. States must develop a total maximum daily load (TMDL) for each pollutant that contributes to the impairment of a listed water body. The Texas Commission on Environmental Quality (TCEQ) is responsible for ensuring that TMDLs are developed for impaired surface waters in Texas.

A TMDL is like a budget—it determines the amount of a particular pollutant that a water body can receive and still meet its applicable water quality standards. TMDLs are the best possible estimates of the assimilative capacity of the water body for a pollutant under consideration. A TMDL is commonly expressed as a load with units in mass per period of time, but may be expressed in other ways. In addition to the TMDL, an implementation plan is developed, which is a description of the regulatory and voluntary measures necessary to improve water quality and restore full use of the water body.

The TMDL Program is a major component of Texas's overall process for managing the quality of its surface waters. The program addresses impaired or threatened streams, reservoirs, lakes, bays, and estuaries (water bodies) in, or bordering on, the state of Texas. The primary objective of the TMDL Program is to restore and maintain the beneficial uses—such as drinking water supply, recreation, support of aquatic life, or fishing—of impaired or threatened water bodies.

TCEQ first identified bacteria impairment within Hillebrandt Bayou in the 2010 edition of the *Texas Integrated Report of Surface Water Quality for the Clean Water Act Sections 305(b) and 303(d)List* (Texas Integrated Report, TCEQ, 2011). The bacteria impairments have been identified in each subsequent edition through 2020.

This document will consider one bacteria impairment in one assessment unit (AU) of Hillebrandt Bayou. The impaired water body and identifying AU number is shown below:

- Hillebrandt Bayou 0704_02

1.2. Water Quality Standards

To protect public health, aquatic life, and development of industries and economies throughout Texas, water quality standards were established by TCEQ. The water quality standards specifically protect appropriate uses for each segment and list appropriate limits for water quality indicators to assure water quality and attainment of uses. TCEQ assesses water body segments based on the water quality standards and publishes the Texas Integrated Report biennially.

The *Texas Surface Water Quality Standards* (TCEQ, 2018a) are rules that:

- designate the uses, or purposes, for which the state's water bodies should be suitable;
- establish numerical and narrative goals for water quality throughout the state; and
- provide a basis on which TCEQ regulatory programs can establish reasonable methods to implement and attain the state's goals for water quality.

Standards are established to protect uses assigned to water bodies. The primary uses assigned in the *Texas Surface Water Quality Standards* to water bodies are:

- aquatic life use
- contact recreation
- domestic water supply
- general use

Fecal indicator bacteria (FIB) are indicators of the risk of illness during contact recreation (e.g., swimming) from ingestion of water. FIB are bacteria that are present in the intestinal tracts of human and other warm-blooded animals. The presence of these bacteria indicates that associated pathogens from fecal wastes may be reaching water bodies, because of such sources as inadequately treated sewage, improperly managed animal waste from livestock, pets in urban areas, aquatic birds, wildlife, and failing septic systems (TCEQ, 2006). *Escherichia coli* (*E. coli*) is a member of the fecal coliform bacteria group and is used in the state of Texas as the FIB in freshwater.

On February 7, 2018, TCEQ adopted revisions to the *Texas Surface Water Quality Standards* (TCEQ, 2018a) and on May 19, 2020, the U.S. Environmental Protection Agency (USEPA) approved the categorical levels of recreational use and their associated criteria. Recreational use consists of five categories:

- Primary contact recreation 1 is that with a significant risk of ingestion of water (such as swimming), and has a geometric mean criterion for *E. coli* of 126 colony forming units (cfu) per 100 milliliters (mL) and an additional single sample criterion of 399 cfu per 100 mL;
- Primary contact recreation 2 includes activities that involve a significant risk of ingestion of water (i.e. swimming, diving, wading and whitewater sports), but occurs less frequently than for primary contact recreation 1 due to physical characteristics of the water body or limited public access. The geometric mean for the standard is 206 cfu/ 100 mL.
- Secondary contact recreation 1 covers activities with limited body contact and a less significant risk of ingestion of water (such as fishing), and a geometric mean criterion for *E. coli* of 630 cfu per 100 mL;
- Secondary contact recreation 2 is similar to secondary contact 1, but activities occur less frequently. It has a geometric mean criterion for *E. coli* of 1,030 cfu per 100 mL; and
- Noncontact recreation is that with no significant risk of ingestion of water, where contact recreation should not occur due to unsafe conditions. It has a geometric mean criterion for *E. coli* of 2,060 cfu per 100 mL.

Hillebrandt Bayou (Segment 0704) is a freshwater stream and has a primary contact recreation 1 use. The associated standard for *E. coli* is a geometric mean of 126 cfu per 100 mL.

1.3. Report Purpose and Organization

TCEQ contracted with the Texas Water Resources Institute (TWRI) for the Hillebrandt Bayou TMDL project. The tasks of this project were to (1) acquire existing (historical) data and information necessary to support assessment activities; (2) perform the appropriate activities necessary to allocate *E. coli* loadings; and (3) assist TCEQ in preparing the TMDL.

This project used historical bacteria and flow data to (1) review the characteristics of the watershed and explore potential sources of *E. coli* for the impaired AU; (2) develop an appropriate tool for development of a bacteria TMDL for the impaired AU; and (3) submit the draft and final technical support document for the impaired AU. The purpose of this report is to provide technical documentation and supporting information for developing the bacteria TMDL for the Hillebrandt Bayou AU 0704_02 watershed. This report contains:

- information on historical data,
- watershed characteristics,
- summary of historical bacteria data that confirm the State of Texas 303(d) listings of impairment due to the presence of FIB (*E. coli*),
- development of load duration curves (LDCs), and
- application of the LDC approach for the pollutant load allocation process.

Section 2. Historical Data Review and Watershed Properties

2.1. Description of Study Area

Hillebrandt Bayou is located near the East Texas Gulf Coast, and runs from the City of Beaumont south to Taylor Bayou (Figure 1). Hillebrandt Bayou consists of a single segment (0704) and two AUs (0704_01 and 0704_02). Hillebrandt Bayou begins in the city of Beaumont approximately 100 meters upstream of State Highway 124 and flows approximately 14.6 miles southeasterly until converging with Taylor Bayou. This document will consider the contact recreation use impairment of the upstream AU of Hillebrandt Bayou (0704_02). The drainage area for AU 0704_02 is 36.02 square miles (23,053.76 acres) and is located entirely in Jefferson County.

The 2020 Texas Integrated Report (TCEQ, 2020) provides the following segment and AU descriptions:

- Segment 0704 (Hillebrandt Bayou) – From the confluence of Taylor Bayou in Jefferson County to a point 100 meters (110 yards) upstream of SH 124 in Jefferson County.
  - AU 0704_02 - From the confluence with Willow Marsh Bayou (0704A) upstream to a point 100 meters (110 yards) upstream of SH 124 in Jefferson County.
  - AU 0704_01 - From the confluence with Taylor Bayou Above Tidal (0701) upstream to confluence with Willow Marsh Bayou (0704A).

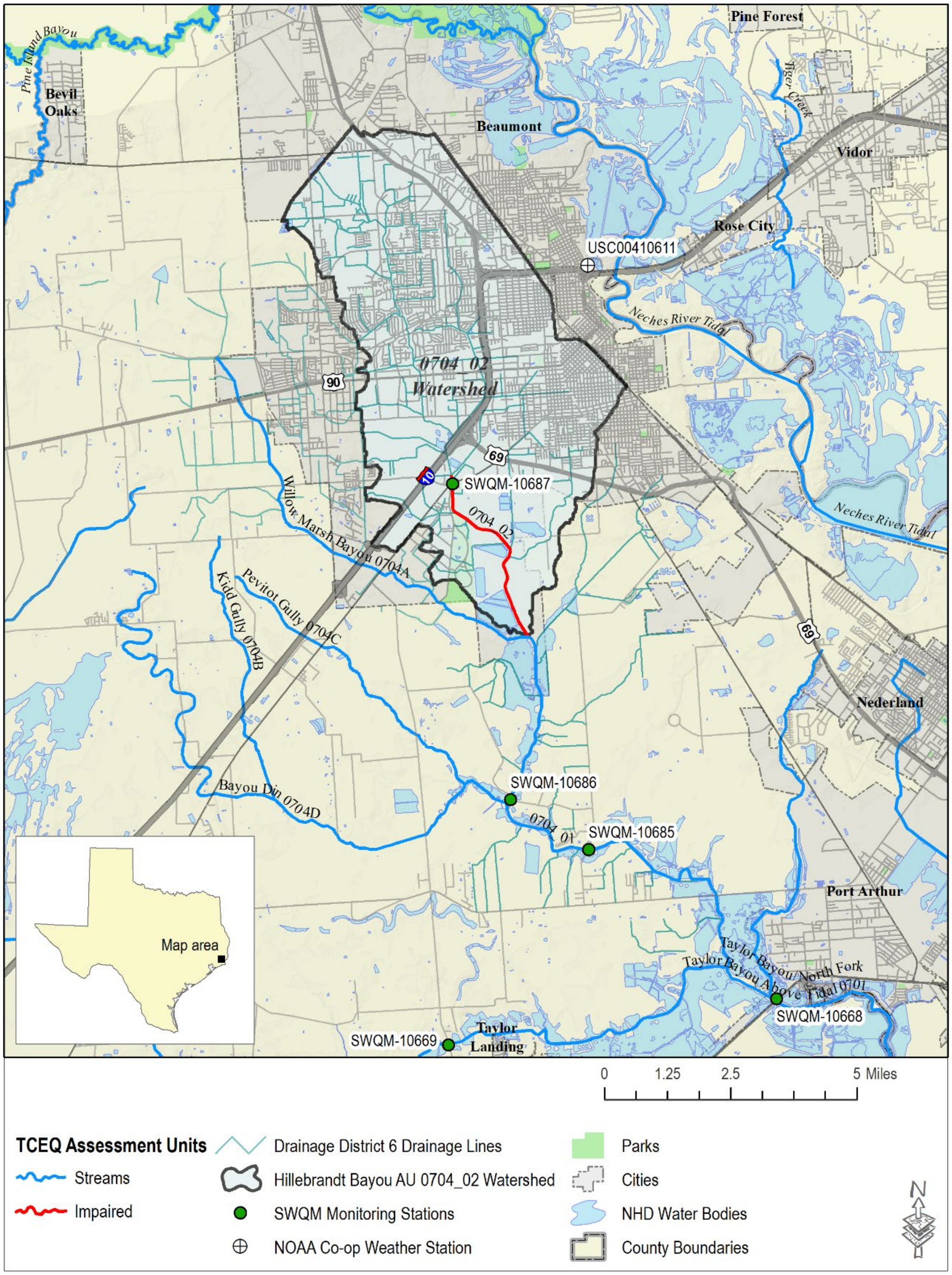

Figure 1. Overview map of the Hillebrandt Bayou AU 0704_02 watershed
Sources: TCEQ Monitoring Station Locations (TCEQ, 2018b), TCEQ Assessment Units (TCEQ 2015b), Drainage Lines (Jefferson County Drainage District No. 6 2019), National Hydrography Dataset (NHD) Water Bodies (USEPA and USGS 2012).

2.2. Review of Routine Monitoring Data for TMDL Watershed

2.2.1. Data Acquisition

All available ambient *E. coli* data records as of April 22, 2019, were obtained from TCEQ Surface Water Quality Monitoring Information System (SWQMIS) database (TCEQ, 2019a). The data represented all historical ambient *E. coli* data and field parameters collected in the project area. Fifty-seven ambient *E. coli* measurements were available at one water quality monitoring station (10687) from October 2005 through November 2018.

2.2.2. Analysis of Bacteria Data

Water quality monitoring has occurred at a single TCEQ surface water quality monitoring (SWQM) station (10687) within Hillebrandt Bayou AU 0704_02 (Figure 1). *E. coli* data collected at this station over the seven-year period of December 1, 2005 to November 30, 2012, were used in assessing attainment of the primary contact recreation use as reported in the 2020 Texas Integrated Report (TCEQ, 2020). The 2020 assessment data indicate non-support of the primary contact recreation use because the geometric mean concentrations exceeded the geometric criterion of 126 cfu/100mL, as summarized in Table 1. In this report, cfu and most probable number (MPN) are considered interchangeable equivalent units of measurement.

Table 1. 2020 Texas Integrated Report Summary for Hillebrandt Bayou (AU 0704_02).

Water Body	AU	Parameter	Station	Data Range	Number of Samples	Station Geometric Mean (cfu/100mL)
Hillebrandt Bayou	0704_02	*E. coli*	10687	12/01/2011 – 11/30/2018	29	455.13

2.3. Watershed Climate and Hydrology

The nearest active weather station, City of Beaumont station USC00410611 (Figure 1), was used to retrieve temperature and precipitation data from 2005 through 2018 (NOAA, 2019). The highest average monthly precipitation occurs in July at 7.8 inches and the lowest average monthly precipitation occurs in October at 3.5 inches (Figure 2). The highest average monthly maximum temperatures occur in August (93.2° F) and the lowest average monthly minimum temperatures occur in January (42.9° F) (Figure 2). From 2005 through 2018, the mean annual precipitation was 62.1 inches, with a low of 34 inches occurring in 2011 and high of 93.4 inches occurring in 2017 (Figure 3).

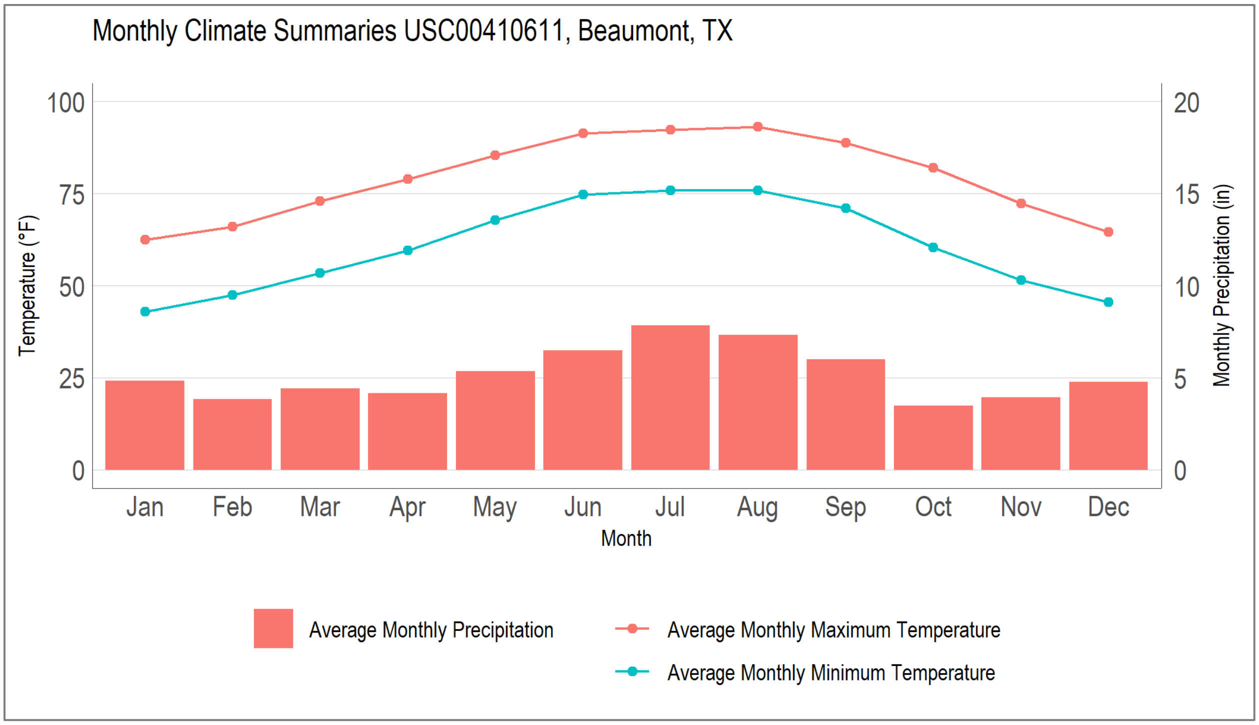

Figure 2. Average monthly temperature and precipitation (2005-2018) at Beaumont, TX Station USC00410611.
Source: NOAA (2019).

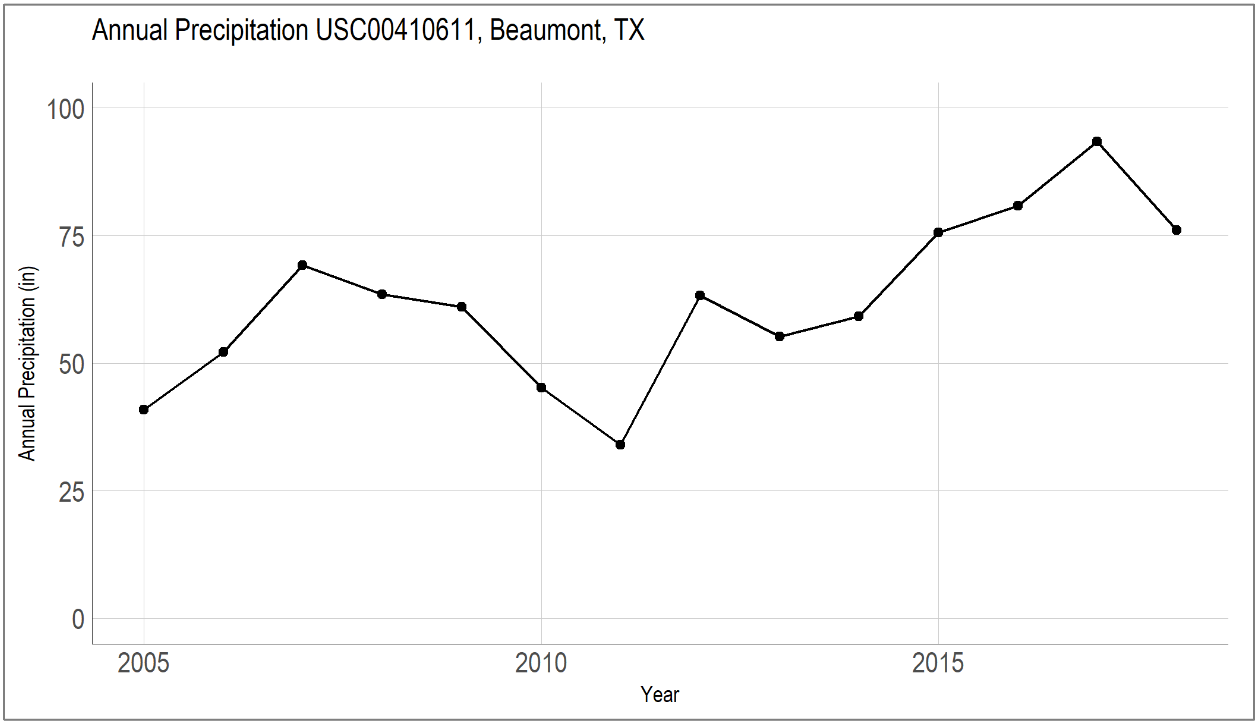

Figure 3. Annual precipitation (2005-2018) at Beaumont, TX Station USC00410611.
Source: NOAA (2019).

2.4. Watershed Population and Population Projections

Watershed population estimates were developed using 2010 U.S. Census block data (USCB, 2010). Census blocks are the smallest geographic units used by USCB to tabulate population data. The Hillebrandt Bayou AU 0704_02 watershed includes 1,743 census blocks, located entirely or partially in the watershed. Population was estimated for those census blocks partially located in the watershed by multiplying the census block population and the percent of each block within each AU watershed. It was assumed for this estimation that populations were evenly distributed within a census block. These estimated partial census block populations were then summed with the populations from the census blocks located entirely within the TMDL watershed. Using this methodology, Hillebrandt Bayou AU 0704_02 watershed population is estimated at 61,273 (Figure 4).

Texas Water Development Board (TWDB) Regional Water Plan Population Projections (TWDB, 2019) provided population projections for the Beaumont Water User Group (WUG) data (Table 2). These population projections indicate a 39.5 percent population increase for the Beaumont WUG from 2020 through 2070. The decadal proportional increases from the Beaumont WUG were applied to the estimated 2010 watershed population to estimate future total population (Table 3). These watershed population projections are consistent with, the 39.5 percent population increase developed by TWDB for the Beaumont WUG from 2020 through 2070.

Table 2. Beaumont Water User Group population projections. Source: 2010 US Census (USCB, 2010) and TWDB Regional Water Plan Population Projections by Water User Group in Texas (TWDB, 2019).

Year and Source	Beaumont WUG Population	Proportional Increase from Previous Decade
2010 U.S. Census Population	118,296	NA
2020 TWDB Projection	130,024	0.099141
2030 TWDB Projection	138,409	0.064488
2040 TWDB Projection	147,221	0.063666
2050 TWDB Projection	157,462	0.069562
2060 TWDB Projection	168,758	0.071738
2070 TWDB Projection	181,406	0.074948

Table 3. 2010 population with population projections for the Hillebrandt Bayou AU0704_02 watershed. Source: Estimates developed from 2010 US Census (USCB, 2010) and TWDB Regional Water Plan Population Projections by Water User Group in Texas (TWDB, 2019).

Area	2010 (U.S. Census Population, estimated)	2020	2030	2040	2050	2060	2070	Percent increase (2020-2070)
Hillebrandt Bayou Watershed	61,273	67,348	71,691	76,255	81,559	87,410	93,961	39.5

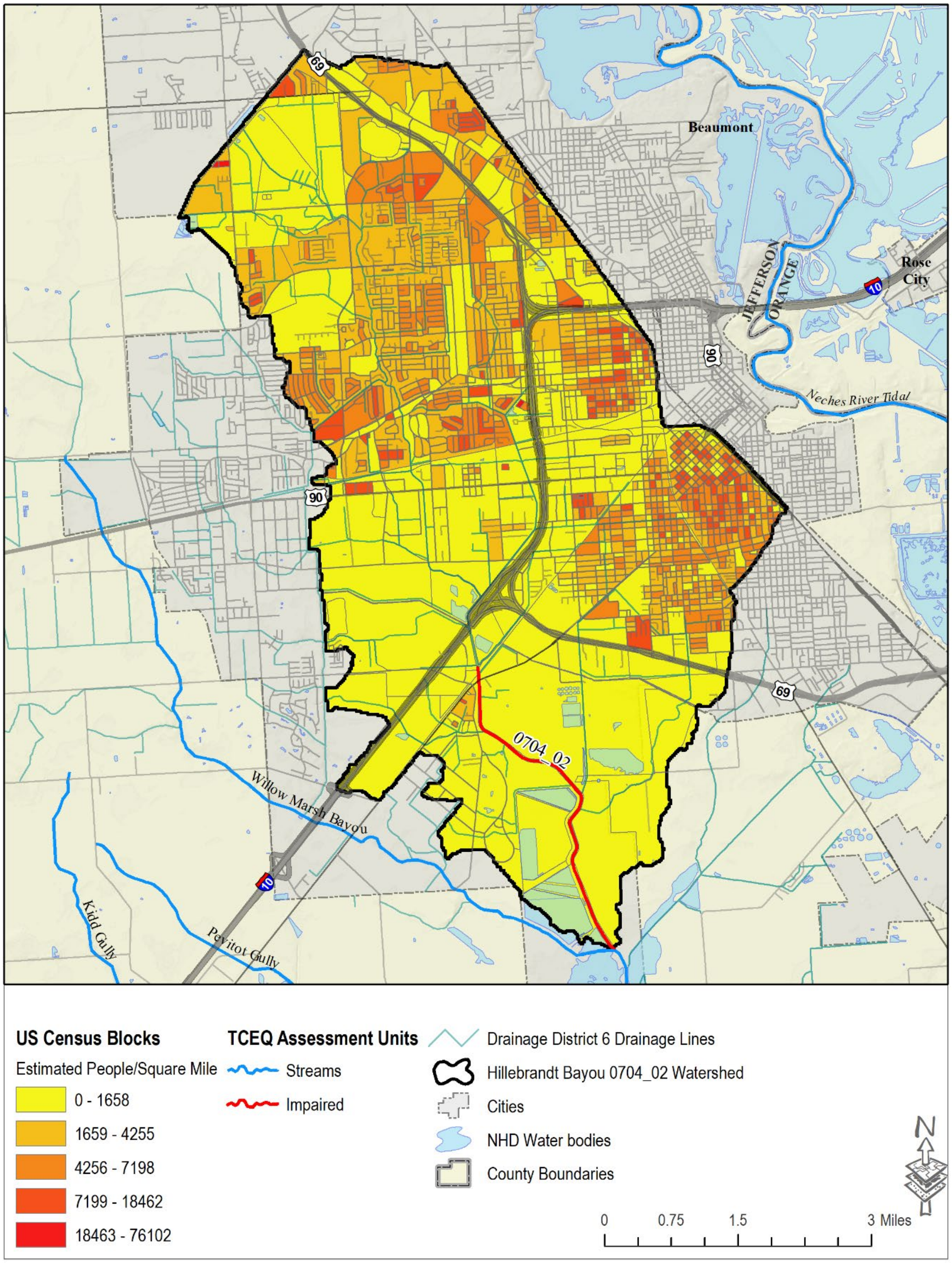

Figure 4. 2010 population estimates by US Census block in the Hillebrandt Bayou AU 0704_02 watershed
Source: USCB (2010)

2.5. Land Cover

Land cover for the watershed were obtained from the 2016 National Land Cover Database (NLCD) (USGS, 2019a), and are displayed in Figure 5. The following categories and definitions represent land cover in the NLCD database:

- Open Water – Areas of open water, generally with less than 25 percent cover of vegetation or soil.
- Developed, Open Space – Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
- Developed, Low Intensity – Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 percent to 49 percent of total cover. These areas most commonly include single-family housing units.
- Developed, Medium Intensity – Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 percent to 79 percent of total cover. These areas most commonly include single-family housing units.
- Developed, High Intensity – Highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 percent to 100 percent of total cover.
- Barren Land (Rock/Sand/Clay) – Areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits, and other accumulations of earthen material. Generally, vegetation accounts for less than 15 percent of total cover.
- Deciduous Forest – Areas dominated by trees generally greater than five meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.
- Evergreen Forest – Areas dominated by trees generally greater than five meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the species maintain their leaves all year. Canopy is never without green foliage.
- Mixed Forest – Areas dominated by trees generally greater than five meters tall, and greater than 20 percent of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent total tree cover.
- Shrub/Scrub – Areas dominated by shrubs; less than five meters tall with shrub canopy typically greater than 20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage, or trees stunted from environmental conditions.
- Grasslands/Herbaceous – Areas dominated by graminoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management such as tilling but can be utilized for grazing.

- Pasture/Hay – Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.
- Cultivated Crops – Areas used to produce annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total vegetation. This class includes all land being actively tilled.
- Woody Wetlands – Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
- Emergent Herbaceous Wetlands – Areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil substrate is periodically saturated with or covered with water.

The total Hillebrandt Bayou AU 0704_02 watershed area is 23,053.76 acres (Table 4) and predominately composed of Developed areas (Open Space, Low, Medium, and High Intensity) land covers (69.56 percent of the watershed). Some Hay/Pasture remains in the less developed portions of the watershed (14.31 percent) and a large amount of wetland and Open Water (13.55 percent) occurs in the watershed.

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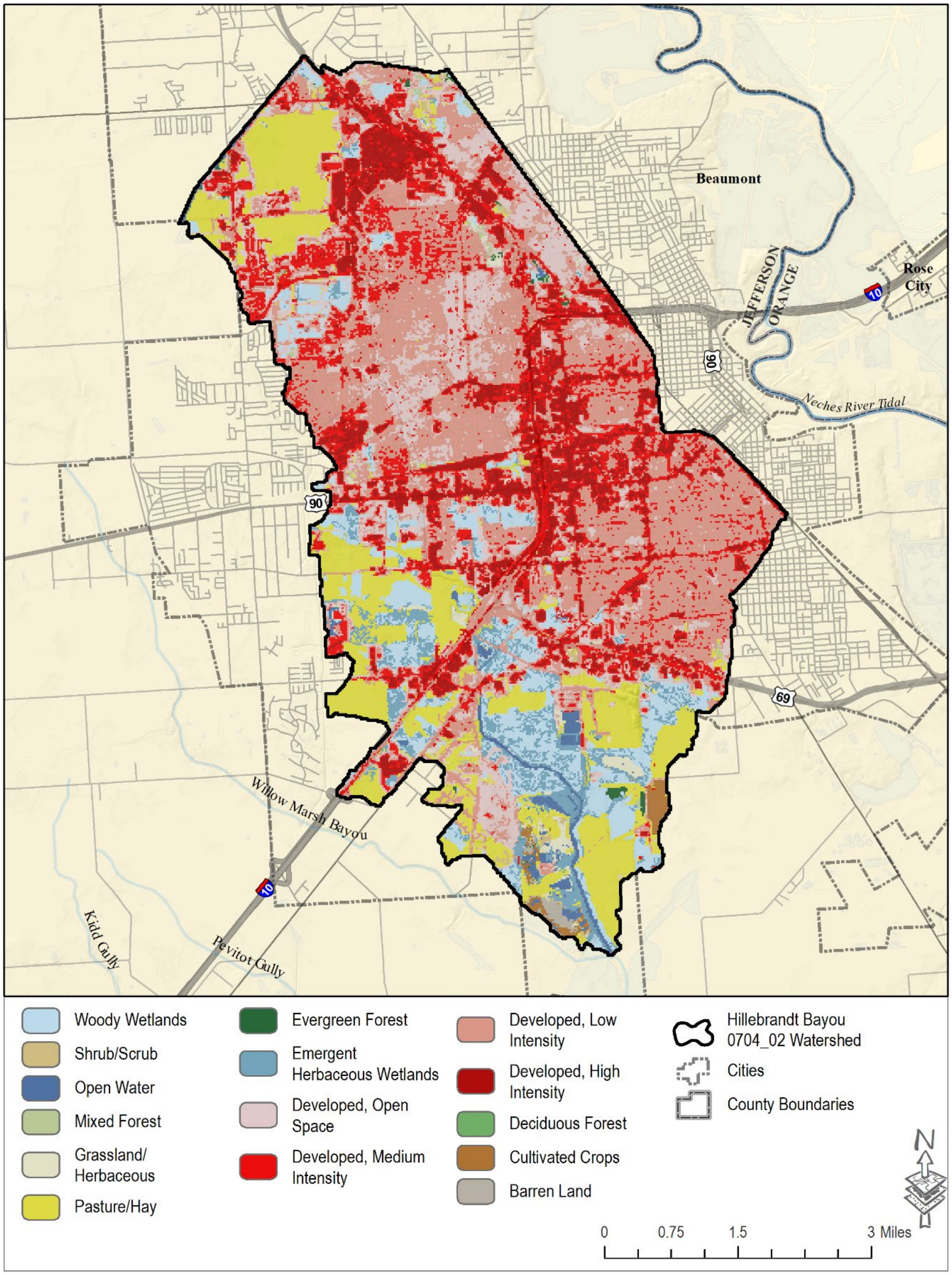

Figure 5. 2016 land cover in the Hillebrandt Bayou AU 0704_02 watershed.
Source: National Land Cover Database (USGS, 2019a)

Table 4. Land cover summary in the Hillebrandt Bayou AU 0704_02 watershed
Source: National Land Cover Database (USGS, 2019a)

Land Cover	Acres	Percent of Total
Open Water	304.00	1.32
Developed, Open Space	2,736.11	11.87
Developed, Low Intensity	7,542.15	32.72
Developed, Medium Intensity	3,537.31	15.34
Developed, High Intensity	2,221.17	9.63
Barren Land	78.45	0.34
Deciduous Forest	0.67	0
Evergreen Forest	46.01	0.20
Mixed Forest	63.44	0.28
Shrub/Scrub	65.67	0.28
Grassland/Herbaceous	198.86	0.86
Pasture/Hay	3,298.73	14.31
Cultivated Crops	142.15	0.62
Woody Wetlands	1,845.92	8.01
Emergent Herbaceous Wetlands	973.14	4.22
Total	**23,053.76[a]**	**100.00**

[a] Rounding results in a slightly different sum from the total watershed area.

2.6. Soils

Soil data was obtained from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (NRCS, 2018). The SSURGO data assigns different soils to one of seven possible runoff potential classifications or hydrologic groups. These classifications are based on the estimated rate of water infiltration when soils are not protected by vegetation, are thoroughly wet, and receive precipitation from long-duration storms. The four main groups are A, B, C, and D, with three dual classes (A/D, B/D, C/D). The SSURGO database defines the classifications below:

- Group A – Soils having high infiltration rate (low runoff potential) when thoroughly wet. These consist mainly of deep, well-drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.
- Group B – Soils having a moderate infiltration rate when thoroughly wet. These consist of moderately deep or deep, moderately well-drained or well-drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission.
- Group C – Soils having a slow infiltration rate when thoroughly wet. These consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.

- Group D – Soils having a very slow infiltration rate (high runoff potential) when thoroughly wet. These consist chiefly of clays that have a high shrink-swell potential, soils that have a high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

Soils with dual hydrologic groupings indicate that drained areas are assigned the first letter, and the second letter is assigned to undrained areas. Only soils that are in group D in their natural condition are assigned to dual classes.

Spatial distribution of soil hydrologic groups within the project watershed is depicted in Figure 6. Within the Hillebrandt Bayou AU 0704_02 watershed, soils are entirely composed of Type D hydrologic groups.

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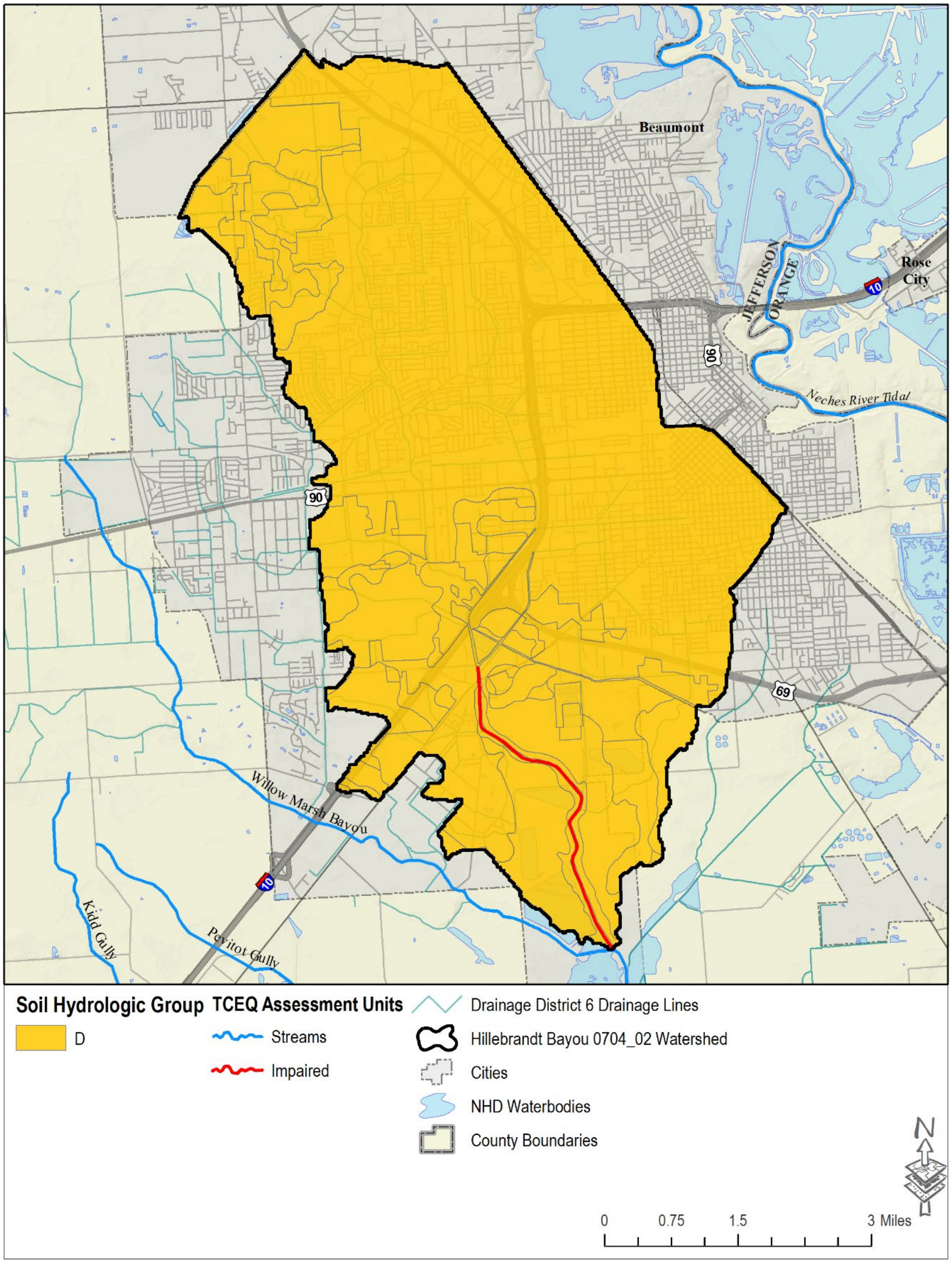

Figure 6. Hydrologic soil groups in the Hillebrandt Bayou AU 0704_02 watershed.
Source: SSURGO database (NRCS, 2018)

2.7. Potential Sources of Fecal Indicator Bacteria

Potential sources of indicator bacteria pollution are divided into two primary categories: *regulated* and *unregulated*. Regulated pollution sources have permits under the Texas Pollutant Discharge Elimination System (TPDES) and National Pollutant Discharge Elimination System (NPDES) programs. Wastewater treatment facility (WWTF) discharges and stormwater discharges from industry, construction, and municipal separate storm sewer systems (MS4s) of cities are examples of regulated sources. Unregulated sources are typically nonpoint source in nature and are not regulated by a permitting system.

With the exception of WWTFs, which receive individual wasteload allocations (Section 4.7.3. Wasteload Allocation), the regulated and unregulated sources in this section are presented to give a general account of the different sources of bacteria expected in the watershed. These source descriptions are not precise inventories and/or loadings.

2.7.1. Regulated Sources

Permitted sources are regulated by permit under the TPDES and NPDES programs. Domestic WWTFs and municipal, construction, and industrial stormwater discharges represent the permitted sources in the Hillebrandt Bayou AU 0704_02 watershed.

2.7.1.1. Domestic and Industrial Wastewater Treatment Facilities

As of April 2019, there is one facility with a TPDES/NPDES permit that operates within the watershed (TCEQ, 2019e; USEPA, 2019). The Hillebrandt WWTF treats domestic wastewater with an interim discharge limit of 31.9 million gallons per day (annual average) and final discharge limit of 46.0 MGD (annual average). Although the Hillebrandt WWTF and treatment wetlands are located within the project watershed, the actual discharge is to a natural wetland that discharges outside of the Hillebrandt Bayou AU 0704_02 watershed slightly downstream of the AU 0704_02 boundary (Figure 7). Therefore, facility discharges are not considered in the AU 0704_02 flow estimation or loading allocations.

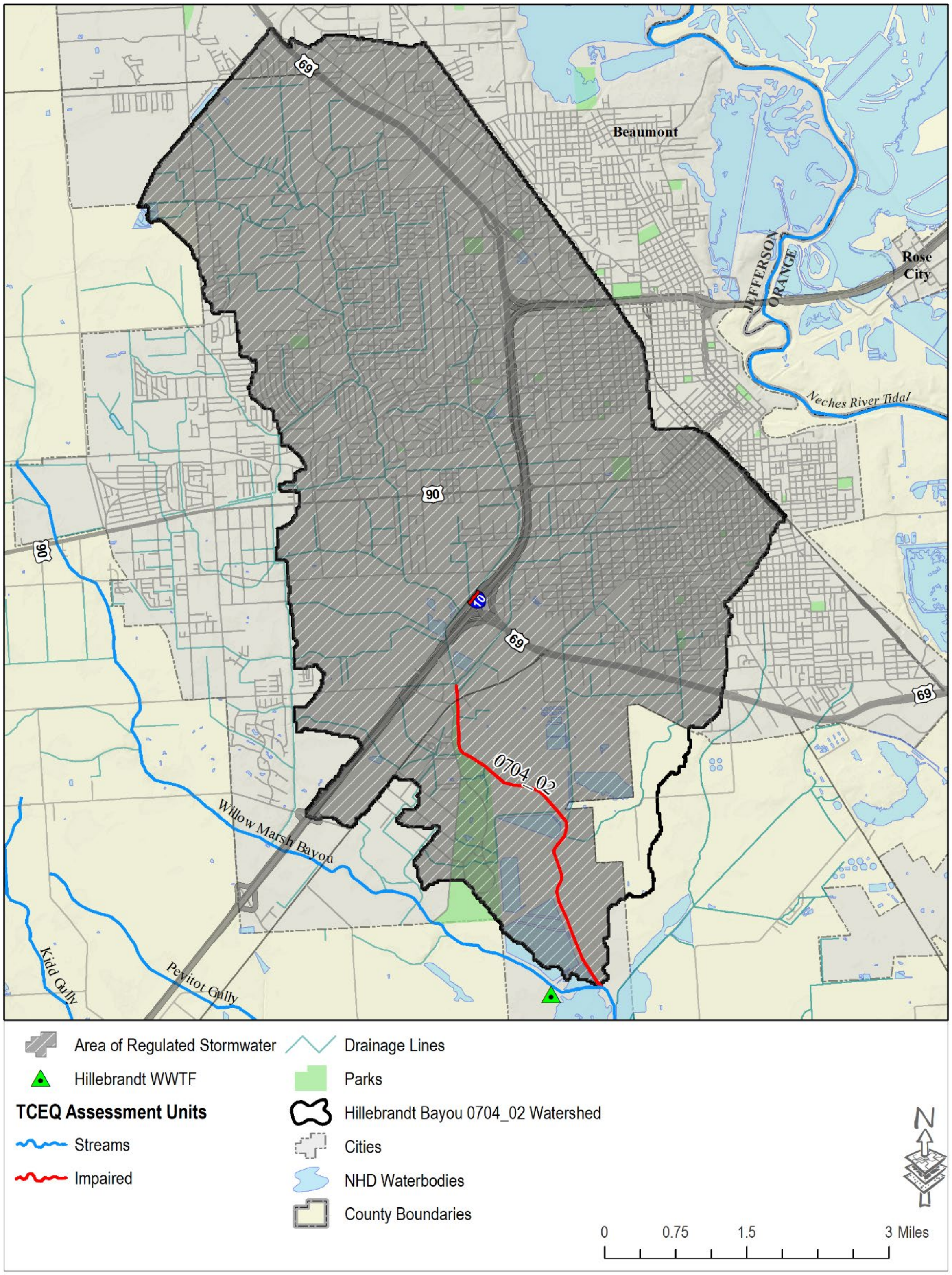

Figure 7. Active permitted sources in the Hillebrandt Bayou AU 0704_02 watershed.
Source: WWTF permits (TCEQ, 2019e), General Permits (TCEQ, 2019f)

2.7.1.2 TPDES General Wastewater Permits

In addition to the individual wastewater discharge permits, discharges of processed wastewater from certain types of facilities are required to be covered by one of several TPDES general permits:

- TXG110000 – concrete production facilities
- TXG130000 – aquaculture production
- TXG340000 – petroleum bulk stations and terminals
- TXG670000 – hydrostatic test water
- TXG830000 – petroleum fuel or petroleum substances
- TXG870000 – pesticides (application only)
- TXG920000 – concentrated animal feeding operations
- WQG100000 – wastewater evaporation
- WQG200000 – livestock manure compost operations (irrigation only)

A review of active general permit coverage (TCEQ, 2019f) in the Hillebrandt Bayou AU 0704_02 watershed as of December 31, 2018, showed a county-wide permit held by Jefferson County Mosquito Control District and a statewide permit held by TPWD under the TXG870000 general permit. These permits do not cover discharge of indicator bacteria and are not expected to have any impact on instream indicator bacteria concentrations. No other general wastewater permits were found for the Hillebrandt Bayou AU 0704_02 watershed.

2.7.1.3. TPDES Regulated Stormwater

When evaluating stormwater for a TMDL allocation, a distinction must be made between stormwater originating from an area under a TPDES or NPDES regulated discharge permit and stormwater originating from areas not under a TPDES or NPDES-regulated discharge permit. Stormwater discharges fall into two categories:

1) stormwater subject to regulation, which is any stormwater originating from a TPDES-regulated Phase I and Phase II MS4, stormwater discharges associated with industrial activities, and stormwater discharges from regulated construction activities; and
2) stormwater runoff not subject to regulation.

The TPDES/NPDES MS4 Phase I and II rules require municipalities and certain other entities in urban areas to obtain permits for their stormwater systems. Both the Phase I and II permits include any conveyance such as ditches, curbs, gutters, and storm sewers that do not connect to a wastewater collection system or treatment facility. Phase I permits are individual permits for large and medium sized communities with populations exceeding 100,000, whereas Phase II permits are for smaller communities within an USCB-defined urbanized area that are regulated by a general permit. The purpose of a MS4 permit is to reduce discharges of pollutants in stormwater to the “maximum extent practicable” by developing and implementing a Stormwater Management Program (SWMP). The SWMPs require specification of best management practices for six 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.

The geographic region of the Hillebrandt Bayou AU 0704_02 watershed covered by Phase I and II MS4 permits is that portion of the area within the jurisdictional boundaries of the regulated entity. Areas under MS4 permits were used to estimate the regulated stormwater areas for construction, industrial, and MS4 permits. The regulated areas under Phase I MS4 permit are based on jurisdictional boundaries of the regulated entity while Phase II MS4 permits are based on U.S. Census Bureau Urbanized Area designation.

TCEQ central registry includes a Phase I MS4 permit held by the City of Beaumont and Jefferson County Drainage District Number 6 that covers the Beaumont jurisdictional boundaries and a statewide MS4 permit held by Texas Department of Transportation that covers the Beaumont Urbanized Area as designated by the USCB (Figure 7, Table 5). These permits cover approximately 35 square miles or 97 percent of the Hillebrandt Bayou AU 0704_02 watershed.

Table 5. TPDES and NPDES MS4 permits in the Hillebrandt Bayou AU 0704_02 watershed.

Entity	TPDES Permit	NPDES Permit
City of Beaumont and Jefferson County Drainage District No. 6	WQ0004637000	TXS000501
Texas Department of Transportation	WQ0005011000	TX002101

2.7.1.4. Sanitary Sewer Overflows

Sanitary sewer overflows (SSOs) are unauthorized discharges that must be addressed by the responsible party, either the TPDES permittee or the owner of the collection system that is connected to a permitted system. SSOs in dry weather most often result from blockages in the sewer collection pipes caused by tree roots, grease, and other debris. Inflow and infiltration (I&I) are typical causes of SSOs under conditions of high flow in the WWTF system. Blockages in the line may exacerbate the I&I problem. Other causes, such as a collapsed sewer line, may occur under any condition.

TCEQ Central Office in Austin provided statewide data on SSO incidents from January 2016 through December 2018 (TCEQ, 2019g) and basin wide data on SSO incidents from 2005 through 2015 (TCEQ, 2019h). Figure 8 shows the density of SSO events across the watershed. The number and volume of SSO incidents by permitted entities in the watershed are included in Table 6.

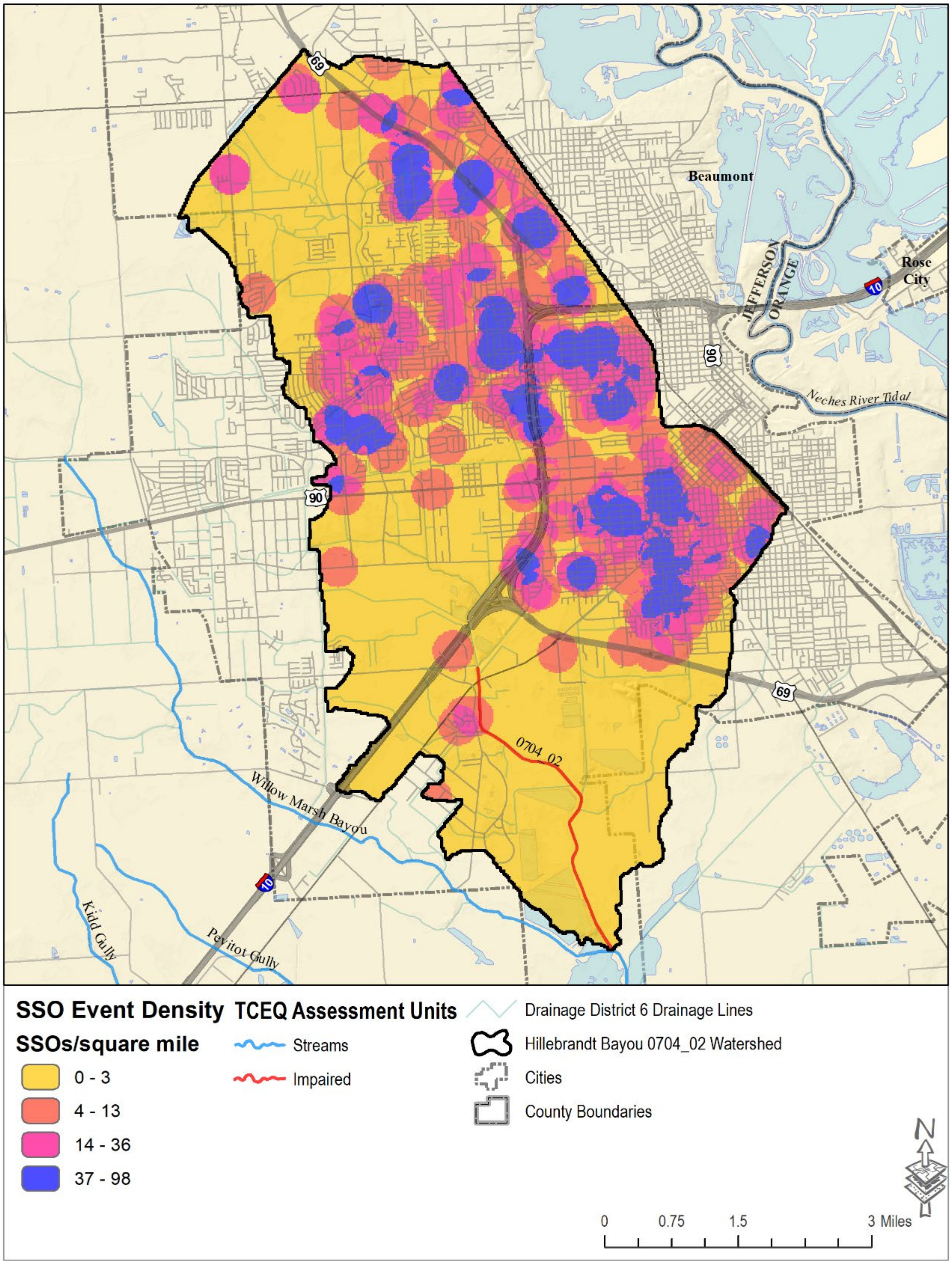

Figure 8. SSO density in the Hillebrandt Bayou AU 0704_02 watershed.
Source: Data files from TCEQ (TCEQ, 2019g; TCEQ, 2019h)

Table 6. Summary of reported SSO events within the Hillebrandt Bayou AU 0704_02 watershed. Source: Data files from TCEQ (TCEQ, 2019g; TCEQ, 2019h)

AU	Estimated Incidents	Total Volume (gallons)	Average Volume (gallons)	Minimum Volume (gallons)	Maximum Volume (gallons)
0704_02[a]	404	174,590	435	1	60,000

[a] Average volume does not equal the total volume divided by the number of incidents due to some events missing a volume spilled in the report.

2.7.2. Unregulated Sources

Unregulated sources include non-permitted, typically nonpoint source, discharges that can contribute to fecal bacteria loading in the watershed. Potential sources, detailed below, include wildlife, agricultural runoff, and domestic pets.

2.7.2.1. Wildlife and Unmanaged Animal Contributions

FIB 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. Riparian corridors of streams and rivers naturally attract wildlife. With direct access to the stream channel, direct deposition of wildlife waste can be a concentrated source of bacteria loading to a water body. Wildlife also deposit fecal bacteria onto land surfaces, where rainfall runoff may wash bacteria into nearby streams.

The Texas Parks and Wildlife Department (TPWD) provided deer population-density estimates by Resource Management Unit (RMU) and Ecoregion in the state (TPWD, 2018). The Hillebrandt Bayou AU 0704_02 watershed lies within RMU 13, with an average deer density of 208.46 acres per deer over the period 2005-2016. Based on 6,635 acres of habitable land in the watershed (land classified in the 2016 NLCD as cultivated crops, pasture/hay, shrub/scrub, grasslands/herbaceous, deciduous forest, evergreen forest, mixed forest, woody wetlands, and emergent herbaceous wetlands), there are an estimated 32 deer in the watershed (Table 7).

AgriLife Extension (2012) estimates one hog per 39 acres as a statewide average density for feral hogs. This density was applied to land classified in the 2016 NLCD as cultivated crops, pasture/hay, shrub/scrub, grasslands/herbaceous, deciduous forest, evergreen forest, mixed forest, woody wetlands, and emergent herbaceous wetlands. Based on 6,635 acres of habitable land, there are an estimated 170 feral hogs in the watershed (Table 7).

Table 7. Estimated deer and feral hog populations in the Hillebrandt Bayou AU 0704_02 watershed Sources: AgriLife Extension (2012); TPWD (2017).

AU	Estimated Number of Deer	Estimated Number of Feral Hogs
0704_02	32	170

2.7.2.2. Unregulated Agricultural Activities and Domesticated Animals

Activities, such as livestock grazing close to water bodies and farmers’ use of manure as fertilizer, can contribute FIB to nearby water bodies. We estimated watershed livestock counts using county-level data available from the 2017 Census of Agriculture (USDA, 2019). The county-level data were refined to reflect acres of grazeable land within the TMDL watershed. The refinement was determined by the area classified as pasture/hay and grassland/herbaceous in the watershed divided by the total area of the county classified as pasture/hay and grassland/herbaceous. The ratio of grazeable acres was multiplied by USDA county level livestock estimates. The watershed level estimates are in Table 8.

Table 8. Livestock estimates in the Hillebrandt Bayou AU 0704_02 watershed
Source: Estimates derived from USDA Census of Agriculture (USDA, 2019).

AU	Cattle and Calves	Hogs and Pigs	Goats and Sheep	Horses
0704_02	661	9	14	17

Pets can also be a source of FIB because stormwater runoff carries the animal wastes into streams. The American Veterinary Medical Association (AVMA) estimates there are 0.584 dogs and 0.638 cats per American household (AVMA, 2012). The number of domestic cats and dogs in the watershed was estimated by applying the AVMA estimates to the number of households in the watershed. The number of watershed households was estimated with 2010 Census Block household counts, multiplied by the proportion of the Census Block within the watershed. Table 9 summarizes the estimated number of pets in the project watershed.

Table 9. Estimated number of households and pet populations in the Hillebrandt Bayou AU 0704_02 watershed.
Source: Estimates derived from USCB Census blocks (USCB, 2010) and AVMA household pet estimates (AVMA, 2012).

AU	Estimated Number of Households	Estimated Dog Population	Estimated Cat Population
0704_02	28,056	16,385	17,900

2.7.2.3. Failing On-Site Sewage Facilities

Private residential on-site sewage facilities (OSSFs), commonly referred to as septic systems, consist of various designs based on physical conditions of the local soil. Typical designs consist of 1) one or more septic tanks and a drainage or distribution field (anaerobic system) and 2) aerobic systems that have an aerated holding tank and often an above-ground sprinkler system for distributing the liquid. In simplest terms, household waste flows into the septic tank or aerated tank, where solids settle out. The liquid portion of the water flows to the distribution system, which may consist of buried perforated pipes or an above-ground sprinkler system.

Several pathways of the liquid waste in OSSFs afford opportunities for bacteria to enter ground and surface waters if the systems are not properly operating. However, properly designed and operated OSSFs are expected to contribute virtually no fecal bacteria to surface waters. For example, it is reported that less than 0.01 percent of fecal coliforms originating in household wastes move further than 6.5 feet down gradient of the drainfield of a septic system (Weiskel, 1996). The estimated OSSF failure rate in this region of Texas is about 12 percent (Reed, Stowe, and Yanke, 2001).

Based on Certificate of Convenience and Necessity (CCN) maps, most of the Hillebrandt Bayou AU 0704_02 watershed (Figure 9) is within the service area of a centralized wastewater collection and treatment system (City of Beaumont Hillebrandt WWTF WQ0010501020). The CCN area is the geographic area under which a public utility has exclusive rights to provide sewer or water service (Public Utility Commission of Texas, 2017). The southern portion of the watershed is not in a wastewater service area. Estimates of the number of OSSFs in the south portion of the project watershed were determined using TCEQ and Texas A&M AgriLife draft coastal zone OSSF database (TCEQ 2019i). Based on this data, there are an estimated four OSSFs within the watershed (Figure 9).

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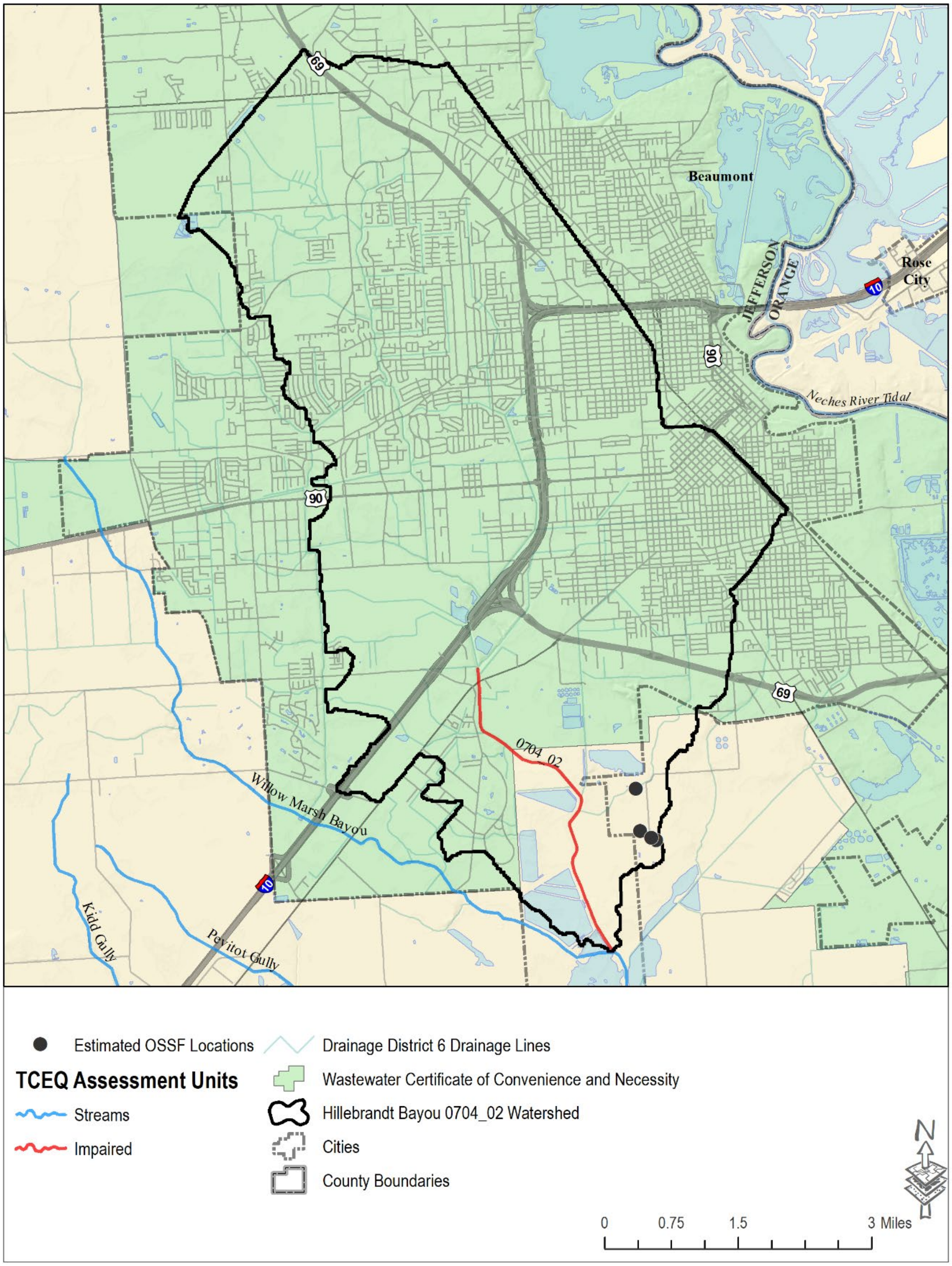

Figure 9. Estimated OSSF locations in the Hillebrandt Bayou AU 0704_02 watershed.
Source: Estimates derived from draft coastal zone OSSF database (TCEQ, 2018c) and CCN data (Public Utility Commission of Texas, 2017).

2.7.2.4. Bacteria Survival and Die-off

Bacteria are living organisms that survive and die. Certain enteric bacteria can survive and replicate in organic materials if appropriate conditions prevail (e.g., warm temperature). Fecal organisms can survive and replicate from improperly treated effluent during their transport in pipe networks, and they can survive and replicate in organic-rich materials such as compost and sludge. While die-off of indicator bacteria has been demonstrated in natural water systems due to the presence of sunlight and predators, the potential for their re-growth is less well understood. Both processes (replication and die-off) are instream processes and are not considered in the bacteria source loading estimates in the TMDL watershed.

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Section 3. Bacteria Tool Development

This section describes the rationale of the bacteria tool selection for TMDL development and details the procedures and results of LDC development.

3.1. Tool Selection

The TMDL allocation process for bacteria involves assigning bacteria, e.g., *E. coli*, loads to their sources such that the total loads do not violate the pertinent numeric criterion protecting contact recreation use. To perform the allocation process, a tool must be developed to assist in allocating bacteria loads. Selection of the appropriate bacteria tool for the impaired AU in the TMDL watershed considered the availability of data and other information necessary for the supportable application of the selected tool and guidance in the Texas bacteria task force report (TWRI, 2007). Mechanistic models and empirically derived LDCs are the two approaches commonly used for bacteria TMDLs in Texas.

Mechanistic models, also referred to as process models, are based on theoretical relationships that numerically describe the physical processes that determine streamflows and bacteria concentrations, in addition to other related response variables. Mechanistic models are available that reliably represent streamflow and bacteria response to land use, rainfall, tidal inputs, and other processes. While hydrologic processes integrated within these models are quite robust, the numeric representations of bacteria transport processes are considered less reliable (TWRI, 2007). Painter et al. (2015) also note that while mechanistic bacteria modelling has progressed significantly, the application of these models relies on quite specific watershed information, more than what is required for representation of hydrologic processes. As a result, decisions on input parameters that affect bacteria response must be made by the modeler when the actual numeric values may not be available within an acceptable range of certainty (Painter et al., 2015). However, under circumstances where the governing physical processes are acceptably quantifiable, the mechanistic model provides an understanding of the important biological, chemical, and physical processes of the prototype system and reasonable predictive capabilities to evaluate alternative allocations of pollutant load sources.

The LDC method allows for estimation of existing and allowable loads by utilizing the cumulative frequency distribution of streamflow and measured pollutant concentration data (Cleland, 2003). In addition to estimating stream loads, the LDC method allows for the determination of the hydrologic conditions under which impairments are typically occurring. This information can be used to identify broad categories of sources (point and nonpoint) that may be contributing to the impairment. The LDC method has found relatively broad acceptance among the regulatory community, primarily due to the simplicity of the approach and ease of application. The regulatory community recognizes the frequent information limitations with the bacteria TMDLs that constrain the use of the more powerful mechanistic models. Further, the bacteria task force appointed by TCEQ and Texas State Soil and Water Conservation Board supports the application of the LDC method within their three-tiered approach to TMDL development (TWRI, 2007). The LDC method lacks the predictive capabilities to evaluate alternative allocation approaches to reach TMDL goals, nor can it be used to quantify specific source contributions and instream fate and transport processes. However, the method does provide a means to estimate the difference in bacteria loads and relevant criterion and can give indications of broad sources of the bacteria, i.e., point source and nonpoint source.

3.1.1. Available Data Resources

Streamflow and *E. coli* data availability were used as criteria in the allocation tool selection process. As already mentioned, the necessary information and data are largely unavailable for the study area to allow the adequate definition of many of the physical and biological processes influencing instream bacteria concentrations for mechanistic model application, and these limitations became an important consideration in the allocation tool selection process.

Hydrologic data in the form of daily streamflow records were unavailable in the TMDL watersheds. However, streamflow records are available in the nearby Menard Creek and Cow Bayou watersheds. Streamflow records in both watersheds are collected and made available by the U.S. Geological Survey (USGS), which operates streamflow gages 08031000 (Cow Bayou) and 08066300 (Menard Creek) that were used to develop mean daily streamflow for Hillebrandt Bayou (USGS, 2019b; Table 10). The gages used to develop naturalized streamflow records were chosen due to their proximity (Asquith et al., 2006) suggest less than 100 miles in proximity and minimal streamflow alterations due to permitted discharges and withdrawals. The decision to utilize two stream gages was guided by the presence of a high number of zero flow days in the Cow Bayou streamflow record which were not anticipated to be representative of Hillebrandt Bayou. However, due to its proximity, the days on which streamflow exceedance values occur on Cow Bayou are expected to be representative of days that streamflow exceedance values occur in Hillebrandt Bayou. Further details on source stream gage selection are provided in Appendix A.

Table 10. Basic information on the USGS streamflow gages used for streamflow development

Gage No.	Site Description	Drainage Area (square miles)	Daily Streamflow Record
08031000	Cow Bayou near Mauriceville, TX	88.90	01-01-2005 – 12-31-2018
08066300	Menard Creek near Rye, TX	147.48	01-01-2005 –12-31-2018

Historical ambient *E. coli* data used for the development of LDCs was obtained through TCEQ SWQMIS database (TCEQ, 2019a) (Figure 10, Table 11)

Table 11. Summary of historical bacteria dataset for the Hillebrandt Bayou AU 0704_02 watershed. Source: TCEQ SWQMIS (TCEQ, 2019a*)*

Water Body Name	AU	Station	Station Location	No. of Samples	Data Date Range	Geomean	Percent Exceeding Single Sample Criterion
Hillebrandt Bayou	0704_02	10687	Hillebrandt Bayou at SH 124	57	10/27/2005 – 11/05/2018	398.72	52.63

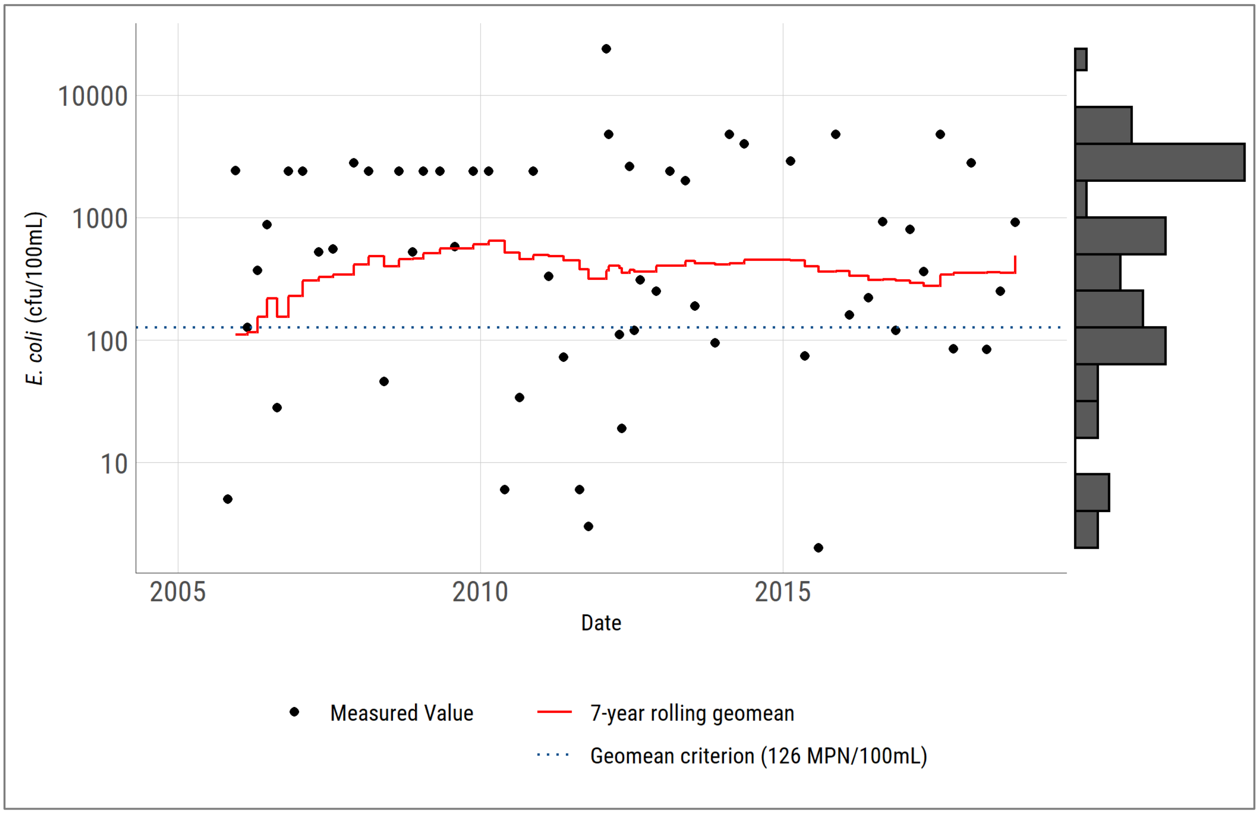

Figure 10. Summary plot of historical bacteria dataset for Hillebrandt Bayou AU 0704_02, including seven-year rolling geometric mean and histogram depicting the distribution of measured values. Source: TCEQ SWQMIS (TCEQ, 2019a)

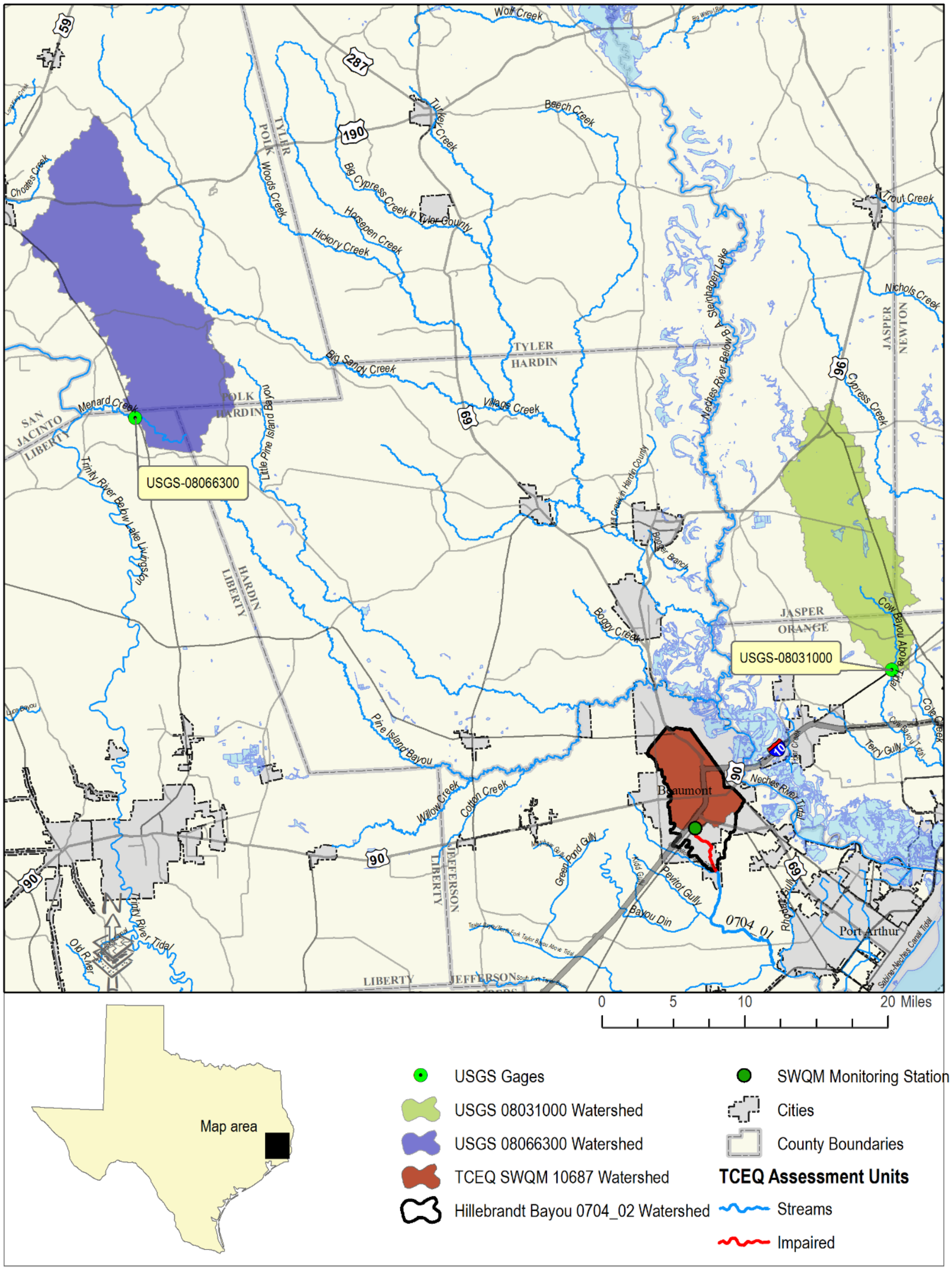

Figure 11. USGS streamflow gages and watersheds used in streamflow development for Hillebrandt Bayou. Sources: USGS Gage Locations (USGS, 2019b), TCEQ Monitoring Station Locations (TCEQ, 2018b), TCEQ Assessment Units (TCEQ, 2015)

3.1.2. Allocation Tool Selection

Watershed-specific data required for the reliable development of bacteria mechanistic models in the Hillebrandt Bayou AU 0704_02 watershed is lacking. In particular, the measured loadings from WWTFs reduce the reliability of any mechanistic model's ability to represent bacteria response (TWRI, 2007). Based on good availability of ambient *E. coli* data and developed daily streamflow records, as well as deficiencies in data to describe bacteria loads and instream processes, the decision was made to use the LDC method as opposed to a mechanistic watershed loading and hydrologic/water quality model.

3.2. Methodology for Flow Duration and Load Duration Curve Development

To develop the flow duration curves (FDCs) and LDCs, the previously discussed data resources were used in the following series of sequential steps.

- Step 1: Determine the hydrologic period of record to be used in developing the FDCs.
- Step 2: Determine the desired stream location for which FDC and LDC development is desired.
- Step 3: Develop drainage area ratio parameter estimates.
- Step 4: Develop daily streamflow record at desired location.
- Step 5: Develop FDC at the desired stream location, segmented into discrete flow regimes.
- Step 6: Develop allowable bacteria LDC at the same stream location based on the relevant criteria and the data from the FDC.
- Step 7: Superimpose historical bacteria data on the allowable bacteria LDC.

Additional information explaining the LDC method may be found in Cleland (2003) and USEPA (2007).

3.2.1. Step 1: Determine Hydrologic Period

Daily hydrologic (streamflow) records were developed from the USGS gage 08031000 at Cow Bayou near Mauriceville, TX and USGS gage 08066300 at Menard Creek near Rye, TX (Figure 11) (USGS, 2019b). These streamflow gages were chosen because of their proximity to the project watersheds and that they represent relatively natural flows with minimal alterations. Menard Creek does not have any permitted dischargers or active water right diversions (TCEQ, 2019c; TCEQ, 2019d). Cow Bayou has one permitted discharger and no active water right diversions. Optimally, the period of record to develop FDCs should include as much data as possible to capture extremes of high and low streamflows and hydrologic variability from high to low precipitation years, but the flow during the period of record selected should also be representative of conditions experienced when the *E. coli* data were collected. We utilized daily mean streamflow records from January 1, 2005 to December 31, 2018. This period of record was selected to capture a reasonable range of extreme high and low streamflow and represents a period in which all the *E. coli* data were collected.

3.2.2. Step 2: Determine Desired Stream Location

For the project water body, there was a single AU with a single water quality monitoring station (10687). The station had 57 *E. coli* samples, meeting the 24 minimum sample suggestion for development of LDCs (TWRI, 2007). The FDC and LDC were developed for station 10687 in Hillebrandt Bayou.

3.2.3. Step 3: Develop Drainage Area Ratio Parameter Estimates

Once the hydrologic period of record and the stream location were determined, the next step was to develop the daily streamflow record for the station. The daily streamflow record was developed from extant USGS records.

The method to develop the necessary streamflow record involved a drainage-area ratio (DAR) approach. With this basic approach, each USGS gage's mean daily streamflow value was multiplied by a factor to estimate flow at the desired SWQM station location (Eq.1).

$$Y=X\left(\frac{A_y}{A_x}\right)^{\phi}$$

(Eq.1)

Where:

Y = streamflow for the ungaged location

X = streamflow for the gaged location

A_y = drainage area for the ungaged location

A_x = drainage area for the gaged location

ϕ = bias correction factor based on streamflow percentile (Asquith et al., 2006)

Often, $\phi = 1$ is used in the DAR approach. However, empirical analysis of streamflows in Texas indicates that $\phi = 1$ results in substantial bias in streamflow estimates at very low and very high streamflow percentiles (Asquith et al, 2006). Based on these observations, values of ϕ are used based on suggestions by Asquith et al. (2006). The value of ϕ varies with streamflow percentiles and lies between 0.7 and 0.935.

A drawback of the DAR approach is that it relies on the assumption of similar hydrology and landcover in the gaged and ungaged watersheds. The Hillebrandt Bayou AU 0704_02 watershed presents additional challenges because it is highly developed (approximately 69 percent), while nearby gaged watersheds are lightly developed. In order to account for the influence of differences in land cover on daily mean streamflows, a parameters estimation procedure was implemented on a modified DAR approach. This approach modifies (Eq.1) to include terms that account for developed and wetland land cover:

$$Y=X\left(\frac{A_y}{A_x}\right)^{\phi} \times \left(\frac{D_y}{D_x}\right)^{\Psi} \times \left(\frac{W_y}{W_x}\right)^{\Omega}$$

(Eq.2)

Where:

Y = streamflow for the ungaged location

X = streamflow for the gaged location

A_y = drainage area for the ungaged location

A_x = drainage area for the gaged location

D_y = developed area for the ungaged location

D_x = developed area for the gaged location

W_y = wetland area for the ungaged location

W_x = wetland area for the gaged location

ϕ, Ψ, Ω = estimated parameters

The method used to estimate the drainage area parameters in (Eq.2) are developed by using an optimization algorithm to fit values Ψ and Ω until the root mean square error between predicted and measured streamflows is minimized. The parameter optimization procedure requires two gaged watersheds with land cover characteristics representative of the surrogate watersheds and Hillebrandt Bayou. The procedure is further explained in Appendix A. The calculated parameters used in this document are:

- Φ = Values vary based on streamflow percentile, values listed in Asquith et al. (2006)
- $\Psi = 1.03037$
- $\Omega = -0.0421$

3.2.4. Step 4: Develop Daily Streamflow Record at Desired Location

After the DAR parameters were estimated, the drainage area ratio formula (Eq.2) was applied to naturalized flows in the gaged watershed. Naturalized flow refers to the flows that would occur absent influences from surface water diversions or discharges. Naturalized mean daily flows were determined in the Cow Bayou watershed by subtracting mean daily discharges reported by the single permitted discharger in the Cow Bayou watershed. When the difference between gaged flows and mean daily discharges was below zero, the value was set to zero. The date of the calculated flow exceedance percentiles in Cow Bayou were assumed to be the same date that a flow exceedance percentile would occur on Hillebrandt Bayou. Naturalized flows in Cow Bayou indicate zero flow occurs approximately eight percent of the days from January 2005 through December 2018. Imagery data suggests Hillebrandt Bayou had at least minimal streamflows during drought periods in 2010 and 2011. Therefore, additional streamflow data was incorporated using Menard Creek (USGS-08066300). Under conditions of uncertainty regarding the hydrology and run-off characteristics of the gaged and ungaged watersheds (as encountered), it is appropriate to apply the mean of the estimated streamflows at a given streamflow percentage (Asquith et al., 2006):

$$Y_p = \frac{X_{1p}(DAR_1) + X_{2p}(DAR_2)}{2}$$

(Eq.3)

Where:

Y_p = streamflow for the ungaged location at streamflow percentile p

X_{1p} = streamflow for the gaged location 1 at streamflow percentile p

X_{2p} = streamflow for the gaged location 2 at streamflow percentile p

DAR_1 = drainage area ratios between gaged location 1 and the ungaged location

DAR_2 = drainage area ratios between gaged location 2 and the ungaged location

Eq. 3 results in a mean daily naturalized streamflow for the ungaged site at a given streamflow percentile (this is essentially the FDC in step 5). By equating the exceedance probabilities at Cow Bayou (the nearest gage) to the exceedance probabilities at Hillebrandt Bayou, the dates of streamflow associated with each exceedance probability at the reference gage were transferred to the ungaged site to construct the final time series of streamflow at the Hillebrandt Bayou. Further details on the application of the DAR methodology and streamflow estimation are in Appendix A.

Finally, naturalized streamflows needed to be adjusted to account for actual permitted dischargers and surface water diversions that occur upstream of the ungaged site. As discussed earlier, no permitted dischargers are in the Hillebrandt Bayou AU 0704_02 watershed. A search of TCEQ active water rights database files revealed that, within the Hillebrandt Bayou AU 0704_02 watershed, there are an estimated two surface water rights owners with diversions at five locations (TCEQ 2019b; TCEQ, 2019c). All of the diversion locations are downstream of the ungaged location; therefore, no further adjustments to the daily streamflow record were considered necessary.

3.2.5. Steps 5 through 7: Flow Duration Curve and Load Duration Curve

FDCs and LDCs are graphs that visualize the percentage of time during which a value of flow or load is equaled or exceeded. To develop an FDC for a location, the following steps were undertaken.

1. Order the daily streamflow data for the location from highest to lowest and assign a rank to each data point (one for the highest flow, two for the second highest flow, and so on);
2. Compute the percent of days each flow was exceeded by dividing each rank by the total number of data points plus one; and
3. Plot the corresponding flow data against exceedance percentages.

Further, when developing an LDC:

- Multiply the streamflow in cubic feet per second (cfs) by the appropriate water quality criterion for *E. coli* (geometric mean of 126 cfu/100 mL or 1.26 cfu/mL) and by a conversion factor (2.44658×10^9), which gives you a loading unit of cfu/day; and
- Plot the exceedance percentages, which are identical to the value for streamflow data points, against the geometric mean criterion for *E. coli*.

The resulting curve represents the maximum daily allowable loadings for the geometric mean criterion. The next step was to plot the measured *E. coli* data on the developed LDC using the following steps:

- Compute the daily loads for each sample by multiplying the measured *E. coli* concentrations on a particular day by the corresponding streamflow on that day and the conversion factor (2.44658×10^9); and
- Plot on the LDC for each station the load for each measurement at the exceedance percentage for its corresponding streamflow.

The plots of the LDC with the measured loads (*E. coli* concentrations times daily streamflow) display the frequency and magnitude at which measured loads exceed the maximum allowable loadings for the geometric mean criterion. Measured loads that are above a maximum allowable loading curve indicate an exceedance of the water quality criterion, while those below a curve show compliance.

3.3. Flow Duration Curve for TMDL Watershed

An FDC was developed for the Hillebrandt Bayou AU 0704_02 watershed at station 10687 (Figure 12). For this report, the FDC was developed by using mean daily streamflows obtained from USGS gages 08031000, 08066300 and period of record (2005-2018), as described in the previous section.

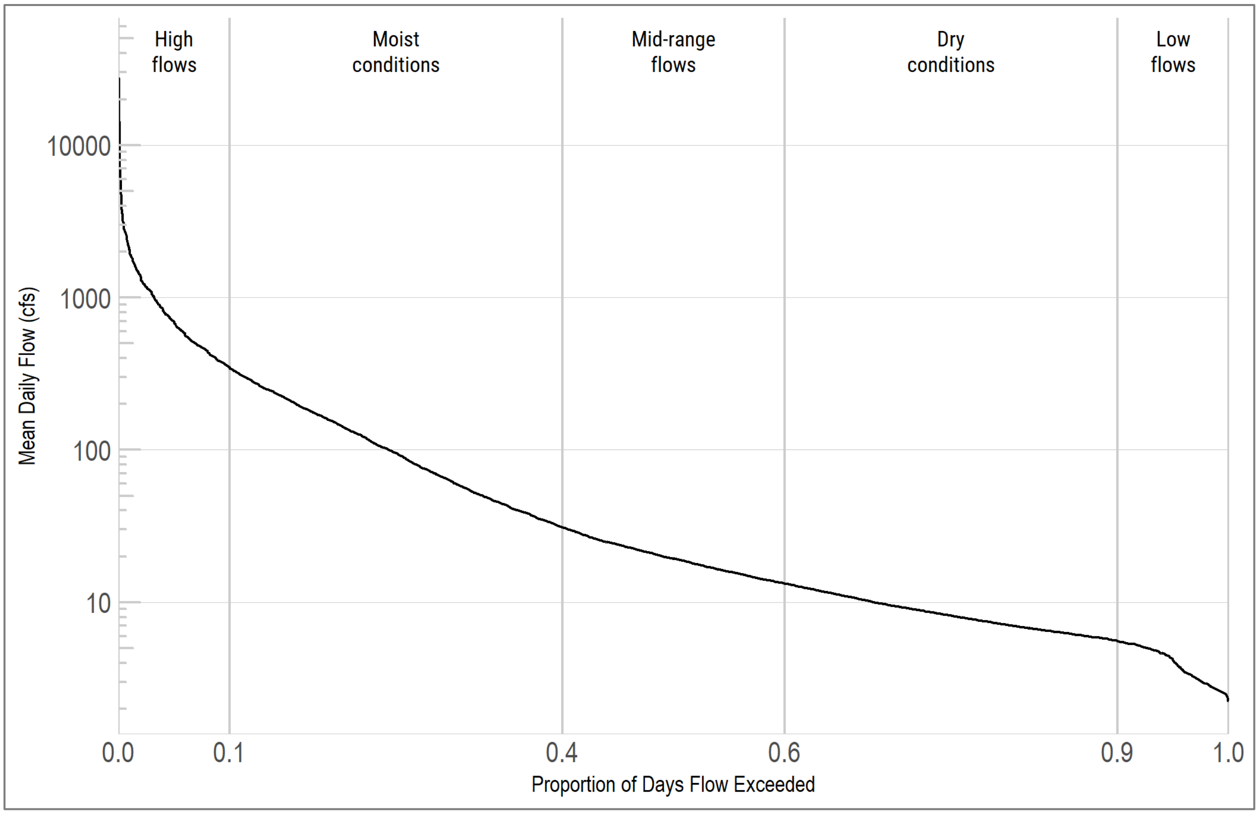

Figure 12. Flow duration curve for Hillebrandt Bayou AU 0704_02 at station 10687

3.4. Load Duration Curve for TMDL Watershed

An LDC was developed for the Hillebrandt Bayou AU 0704_02 watershed at station 10687 using *E. coli* data from TCEQ SWQMIS station 10687. A useful refinement of the LDC approach is to divide the curve into flow-regime regions to analyze exceedance patterns in smaller portions of the duration curves. This approach can assist in determining streamflow conditions under which exceedances are occurring. A commonly used set of regimes that is provided in Cleland (2003) is based on the following five intervals along the x-axis of the FDCs and LDCs: (1) 0-10 percent (high flows); (2) 10-40 percent (moist conditions); (3) 40-60 percent (mid-range flows); (4) 60-90 percent (dry conditions); and (5) 90-100 percent (low flows).

The selection of the flow regime intervals was based on general observation of the developed LDC. Figure 13 depicts the LDC for Hillebrandt AU 0704_02. The geometric mean loading in each flow regime is also shown to aid interpretation.

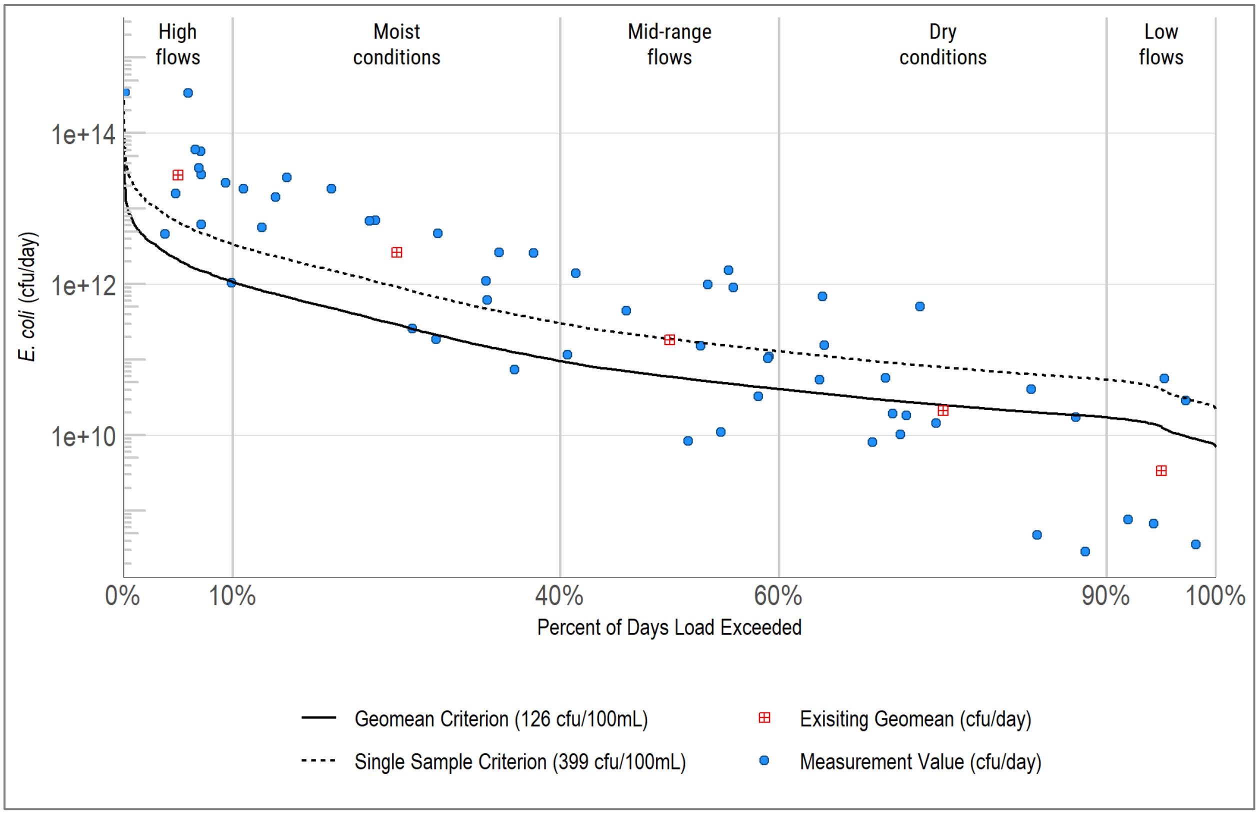

Figure 13. Load duration curve for Hillebrandt Bayou AU 0704_02 at station 10687

Section 4. TMDL Allocation Analysis

4.1. Endpoint Identification

The AU within the TMDL watershed has a use of primary contact recreation, which utilizes a geometric mean numeric criterion of 126 cfu/100 mL for *E. coli* indicator bacteria (TCEQ, 2018a). All TMDLs must identify a quantifiable water quality target that indicates the desired water quality condition and provides a measurable goal for the TMDL. The TMDL endpoint also serves to focus the technical work to be accomplished and as a criterion against which to evaluate future conditions.

The endpoint for the TMDL is to maintain the concentration of *E. coli* below the geometric mean criterion of 126 cfu/100 mL. This endpoint was applied to the AU addressed with this TMDL. This endpoint is identical to the geometric mean criterion for primary contact recreation in the 2018 Surface Water Quality Standards (TCEQ, 2018a).

4.2. Seasonality

Seasonal variations or seasonality occur when there is a cyclic pattern in streamflow and, more importantly, in water quality constituents. Federal regulations in Title 40 Code of Federal Regulations Section 130.7(c)(1) [40 CFR §130.7(c)(1)] require that TMDLs account for seasonal variation in watershed conditions and pollutant loading. The seasonal differences in indicator bacteria concentrations were assessed by comparing *E. coli* samples during warmer months (May-September) against those collected during cooler months (November-March). The months of April and October were considered transitional between warm and cool seasons and were excluded from the seasonal analysis. Differences in seasonal concentrations were then evaluated with a Wilcoxon Rank Sum test (also known as the "Mann-Whitney" test). The Wilcoxon Rank Sum test was chosen for its ability to handle non-normal data without requiring data transformation. The test was considered significant at the $\alpha = 0.05$ level.

The Wilcoxon Rank Sum test suggests there is a seasonal difference in *E. coli* concentrations in Hillebrandt Bayou AU 0704_02 ($W = 142$, $p < 0.01$) (Figure 14). As shown in Figure 14, the distribution of cool season *E. coli* measurements is significantly higher than the distribution of warm season measurements.

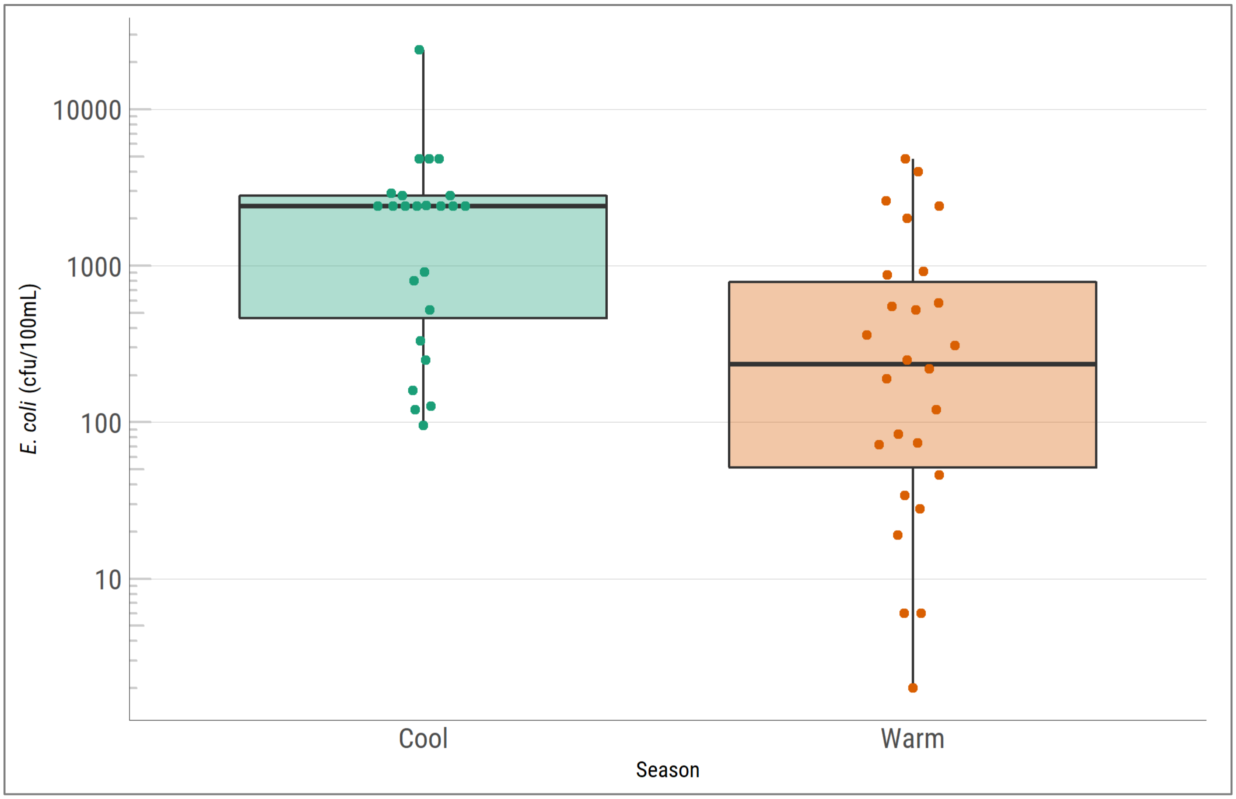

Figure 14. Distribution of *E. coli* concentration by season in Hillebrandt Bayou AU 0704_02 watershed

4.3. Linkage Analysis

Establishing the relationship between instream water quality and the source of loadings is an important component in developing a TMDL. It allows for the evaluation of management options that will achieve the desired endpoint. The relationship may be established through a variety of techniques.

Generally, if high bacteria concentrations are measured in a water body at low to median flows in the absence of runoff events, the main contributing sources are likely to be point sources and direct deposition (such as direct fecal deposition into the water body). During ambient flows, these inputs to the system will increase pollutant concentrations depending on the magnitude and concentration of the sources. As flows increase in magnitude, the impact of point sources like direct deposition is typically diluted, and would, therefore, be a smaller part of the overall concentrations.

Bacteria load contributions from regulated and unregulated stormwater sources are greatest during runoff events. Rainfall runoff, depending upon the severity of the storm, has the capacity to carry indicator bacteria from the land surface into the receiving stream. Generally, this loading follows a pattern of higher concentrations in the water body as the first flush of storm runoff enters the receiving stream. Over time, the concentrations decline because the sources of indicator bacteria are attenuated as runoff washes them from the land surface and the volume of runoff decreases following the rain event.

Load duration curves were used to examine the relationship between instream water quality and the source of indicator bacteria loads. Inherent to the use of LDCs as the mechanism of linkage analysis is the assumption of a direct relationship between pollutant load sources (regulated and unregulated) and instream loads. Further, this one-to-one relationship was also inherently assumed when using LDCs to define the TMDL pollutant load allocation (Section 4.7). The pollutant load allocation was based on the flows associated with the watershed areas under stormwater regulation, and the remaining portion was assigned to the unregulated stormwater.

4.4. Load Duration Curve Analysis

LDC analyses were used to examine the relationship between instream water quality and the broad sources of indicator bacteria loads, and they are the basis of the TMDL allocations. The strength of this TMDL is the use of the LDC method to determine the TMDL allocations. An LDC is a simple statistical method that provides a basic description of the water quality problem. This tool is easily developed and explained to stakeholders and uses available water quality and flow data. The LDC method does not require any assumptions regarding loading rates, stream hydrology, land use conditions, and other conditions in the watershed. The USEPA supports the use of this approach to characterize pollutant sources. In addition, many other states are using this method to develop TMDLs.

The weaknesses of this method include the limited information it provides regarding the magnitude or specific origin of the various sources. Only limited information is gathered regarding point and nonpoint sources in the watershed. The general difficulty in analyzing and characterizing *E. coli* in the environment is also a weakness of this method.

The LDC method allows for estimation of existing and TMDL loads by utilizing the cumulative frequency distribution of streamflow and measured pollutant concentration data (Cleland, 2003). In addition to estimating stream loads, this method allows for the determination of the hydrological conditions under which impairments are typically occurring, can give indications of the broad origins of the bacteria (i.e., point source and stormwater), and provides a means to allocate allowable loadings.

Based on the LDCs to be used in the pollutant load allocation process with historical *E. coli* data added to the graphs (Figure 13) and Section 2.7. Potential Sources of Fecal Indicator Bacteria, the following broad linkage statements can be made.

For the Hillebrandt Bayou (AU 0704_02) watershed, historical *E. coli* data indicate that elevated bacteria loading primarily occurs under high flow, moist conditions, and mid-range flows. However, bacteria loads are most elevated under the highest flow conditions. Under the dry conditions and lowest flow conditions, loadings fall below the geometric mean criterion.

The majority of high flow- and moist condition-related loadings are likely attributed to regulated stormwater that comprises a majority of the watershed. Within the watershed, there are no WWTFs to contribute point source loadings under dry and low flow conditions; however, SSOs are periodic events that may contribute to bacteria loadings within the watershed under wet weather conditions. Other sources of bacteria loadings under mid-range and low flow conditions and in the absence of overland flow contributions (i.e., without stormwater contribution) are most likely to contribute bacteria directly to the water. These sources may include direct deposition of fecal material from sources such as wildlife, feral hogs, birds, and livestock. OSSFs are relatively scarce within the watershed and are unlikely to be a substantial contributor to loading under any flow conditions. However, the actual contributions of bacteria loadings directly attributable to these sources cannot be determined using LDCs.

4.5. Margin of Safety

The margin of safety (MOS) is used to account for uncertainty in the analysis performed to develop the TMDL and thus provides a higher level of assurance that the goal of the TMDL will be met. According to USEPA guidance (USEPA, 1991), the MOS can be incorporated in the TMDL using two methods.

1). Implicitly incorporating the MOS using conservative model assumptions to develop allocations; or

2). explicitly specifying a portion of the TMDL as the MOS and using the remainder for allocations.

The MOS is designed to account for any uncertainty that may arise in specifying water quality control strategies for the complex environmental processes that affect water quality. Quantification of this uncertainty, to the extent possible, is the basis for assigning a MOS.

The TMDL covered by this report incorporates an explicit MOS of five percent.

4.6. Load Reduction Analysis

While the TMDL for the project watershed will be developed using load allocations, additional insight may be gained through a load reduction analysis. A single percent load reduction required to meet the allowable loading for each flow regime was determined using the historical *E. coli* data obtained from the station in the impaired watershed (Table 12). The estimated existing load in each flow regime was calculated with the geometric mean concentration in each flow category and the median flow in each flow category (excluding days with zero flow), as estimated in Section 3.3 (Eq. 4).

$$\text{Existing Load}_{\text{FC}} = \widetilde{\text{Q}}_{\text{FC}} \times \text{G}_{\text{FC}} \times \text{Conversion Factor} \qquad \text{(Eq. 4)}$$

Where:

$\textit{Existing Load}_{FC}$ = Existing bacteria load at the median flow for flow category *FC*
FC = Respective flow category
$\tilde{Q}_{FC}$ = Median flow for flow category *FC*
G_{FC} = Geometric mean of bacteria (cfu *E. coli*/100mL) samples for flow category *FC*
Conversion Factor = 28,316.8 mL/cubic feet (ft^3) × 86,400 seconds/day ÷ 1×10^9

The allowable load (Eq.5) was calculated as:

$$\text{Allowable Load}_{FC} = \tilde{Q}_{FC} \times \text{Criterion} \times \text{Conversion Factor}$$

(Eq.5)

Where:

$\text{Allowable Load}_{FC}$ = Allowable load at the median flow for flow category (FC)
$\tilde{Q}_{FC}$ = Median flow in each flow category
Criterion = 126 cfu/100 mL (*E. coli*)
Conversion Factor = 28,316.8 mL/ft^3 × 86,400 seconds/day ÷ 1×10^9

Percent reduction for each flow category (PR_{FC}) (Eq.6) was then calculated as:

$$PR_{FC} = \frac{(\text{Existing Load}_{FC} - \text{Allowable Load}_{FC})}{\text{Existing Load}_{FC}}$$

(Eq.6)

Table 12. Percent daily load reductions needed to meet water quality standards in each flow regime.

Flow Regime	Flow (cfs)	Geomean Concentration (cfu/100mL)	Existing Load (billion cfu/day)	Allowable Load (billion cfu/day)	Percent Reduction Required
High Flows	681.844	1,662.067	27,726.271	2,101.907	92.4
Moist Conditions	94.974	1,137.906	2,644.046	292.774	88.9
Mid-Range Flows	19.270	386.110	182.033	59.403	67.4
Dry Conditions	8.120	105.780	21.014	25.031	NA
Low Flows	4.171	32.914	3.359	12.858	NA

4.7. Pollutant Load Allocations

A TMDL represents the maximum amount of a pollutant that the stream can receive in a single day without exceeding water quality standards. The pollutant load allocations were calculated using the equation:

$$\text{TMDL} = \text{WLA} + \text{LA} + \text{FG} + \text{MOS}$$

(Eq.7)

Where:

TMDL = total maximum daily load
WLA = wasteload allocation, the amount of pollutant allowed by regulated dischargers
LA = load allocation, the amount of pollutant allowed by unregulated sources
FG = loading associated with future growth from potential regulated facilities
MOS = margin of safety load

As stated in 40 CFR §130.2(1), TMDLs can be expressed in terms of mass per time, toxicity, or other appropriate measures. For *E. coli*, TMDLs are expressed as cfu/day, and represent the maximum one-day load the stream can assimilate while still attaining the standards for surface water quality.

The TMDL component for the impaired AU covered in this report is derived using the median flow within the high flow regime (or five percent flow) of the LDC developed for Hillebrandt Bayou AU 0704_02. For the remainder of this report, each section will present an explanation of the TMDL component first, followed by the results of the calculation for that component.

4.7.1. AU-Level TMDL Calculations

The TMDL for the impaired AU was developed as a pollutant load allocation based on information from the LDC developed for SWQM station 10687 (Figure 10). As discussed in more detail in Section 3, a bacteria LDC was developed by multiplying the streamflow value along the FDC by the primary contact recreation *E. coli* geometric mean criterion (126 cfu/100mL) and by the conversion factor to convert to loading in colonies per day. This effectively displays the LDC as the TMDL curve of maximum allowable loading:

$$\text{TMDL} = \text{Criterion} \times \text{Flow} \times \text{Conversion Factor}$$

(Eq.8)

Where:

Criterion = 126 cfu/100 mL (*E. coli*)
Conversion Factor (to billion cfu/day) = 28,316.8 mL/ft^3 × 86,400 seconds/day÷ 1×10^9

At the five percent load duration exceedance, the TMDL value is provided in Table 13.

Table 13. Summary of allowable loadings for Hillebrandt Bayou AU 0704_02 watershed

AU	5% Exceedance Flow (cfs)	5% Exceedance Load (cfu/day)	TMDL (billion cfu/day)
0704_02	681.844	2.10×10^{12}	2,101.907

4.7.2. Margin of Safety

The MOS is only applied to the allowable loading for a watershed. Therefore, the MOS is expressed mathematically as the following:

$$\text{MOS} = 0.05 \times \text{TMDL}$$

(Eq.9)

Where:

MOS = margin of safety load
TMDL = total maximum daily load

The MOS for AU 0704_02 is presented in Table 14.

Table 14. Summary of MOS calculation for Hillebrandt Bayou 0704_02 watershed

AU	TMDL (billion cfu/day)	MOS (billion cfu/day)
0704_02	2,101.907	105.095

[Remainder of page intentionally left blank]

4.7.3. Wasteload Allocation

The WLA consists of two parts – the wasteload that is allocated to TPDES-regulated WWTFs (WLA_{WWTF}) and the wasteload that is allocated to regulated stormwater dischargers (WLA_{SW}).

$$\mathrm{WLA} = \mathrm{WLA}_{\mathrm{WWTF}} + \mathrm{WLA}_{\mathrm{SW}}$$

(Eq.10)

4.7.3.1. Wastewater (WLA_{WWTF})

TPDES-regulated WWTFs are allocated a daily wasteload (WLA_{WWTF}) calculated as their full regulated discharge flow rate multiplied by the instream geometric mean criterion. The *E. coli* primary contact recreation geometric mean criterion of 126 cfu/100mL is used as the WWTF target. This is expressed as:

$$\mathrm{WLA}_{\mathrm{WWTF}} = \mathrm{Criterion} \times \mathrm{Flow} \times \mathrm{Conversion\ Factor}$$

(Eq.11)

Where:

Criterion = 126 cfu/100mL *E. coli*
Flow = full regulated flow (MGD)
Conversion Factor (to cfu/day) = 1.54723 cfs/MGD × 28,316.8 mL/ft^3 × 86,400 seconds/ per day ÷ 1×10^9

The daily allowable loading of *E. coli* assigned to WLA_{WWTF} was determined to be zero in Hillebrandt Bayou (AU 0704_02) because there are no WWTFs in the watershed; therefore, there are no regulated flows from any WWTFs.

4.7.3.2. Stormwater (WLA_{SW})

Stormwater discharges from MS4, industrial, and construction sites are considered permitted or regulated point sources. Therefore, the WLA calculations must also include an allocation for regulated stormwater discharges (WLA_{SW}). A simplified approach for estimating the WLA_{SW} for the area was used in the development of the TMDL due to the limited amount of data available, the complexities associated with simulating rainfall runoff, and the variability of stormwater loading. The percentage of land area included in the watershed that is under the jurisdiction of stormwater permits is used to estimate the amount of overall runoff load that should be allocated as the regulated stormwater contribution in the WLA_{SW} component of the TMDL. The load allocation (LA) component of the TMDL corresponds to direct nonpoint runoff and is the difference between the total load from stormwater runoff and the portion allocated to WLA_{SW}.

WLA_{SW} is the sum of loads from regulated stormwater sources and is calculated as:

$$\mathrm{WLA_{SW}} = (\mathrm{TMDL} - \mathrm{WLA_{WWTF}} - \mathrm{FG} - \mathrm{MOS}) \times \mathrm{FDA_{SWP}}$$

(Eq.12)

Where:

WLA_{SW} = sum of all regulated stormwater loads
$TMDL$ = total maximum daily load
WLA_{WWTF} = sum of WWTF loads
FG = sum of future growth loads from potential regulated facilities
MOS = margin of safety load
FDA_{SWP} = fractional proportion of drainage area under jurisdiction of stormwater permits

In order to calculate the WLA_{SW} component of the TMDL, the fractional proportion of the drainage under the jurisdiction of stormwater permits (FDA_{SWP}) must be determined to estimate the amount of runoff load that should be allocated to WLA_{SW}. The term FDA_{SWP} was calculated based on the combined area under regulated stormwater permits as described in Section 2.7.1.3. TPDES Regulated Stormwater. The calculated FDA_{SWP} is shown in Table 15.

Table 15. Regulated stormwater acreage and FDA_{swp} calculation for Hillebrandt Bayou 0704_02 watershed

AU	Estimated Area Under Stormwater Regulation (square miles)	Watershed Area (square miles)	FDA_{SWP}
0704_02	35.00	36.02	0.972

The Future Growth (FG) term required to calculate WLA_{SW} is described in the next section. However, the WLA_{SW} calculations are presented in Table 16 for continuity.

Table 16. Regulated stormwater calculations for Hillebrandt Bayou 0704_02 watershed

AU	TMDL†	WLA_{WWTF}†	FG†	MOS†	FDA_{SWP}	WLA_{SW}†
0704_02	2,101.907	0	86.664	105.095	0.972	1,856.664

† in units of billion cfu/day *E. coli*

With the WLA_{SW} and WLA_{WWTF} terms, the total WLA term can be determined using Eq. 10 (Table 17).

Table 17. Wasteload allocation summary for Hillebrandt Bayou 0704_02 watershed

AU	WLA_{WWTF}†	WLA_{SW}†	WLA†
0704_02	0	1,856.664	1,856.664

† in units of billion cfu/day *E. coli*

4.7.4. Future Growth

The FG component of the TMDL equation addresses the requirement of TMDLs to account for future loadings that might occur as a result of population growth, changes in community infrastructure, and development. 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 standard.

To account for the FG component of the impaired AUs, the loadings from WWTFs are included in the FG computation, which is based on the WLA_{WWTF} formula (Eq.11). The FG equation contains an additional term to account for project population growth within WWTF service areas between 2020 and 2070, based on TWDB Regional Water Plan Population and Water Demand Projections (TWDB, 2019) (Eq.13).

$$\text{FG} = \text{Criterion} \times (\%\text{POP}_{2020\text{-}2070} \times \text{WWTF}_{\text{FP}}) \times \text{Conversion Factor}$$

(Eq.13)

Where:

FG = Future growth from existing WWTFs
Criterion = 126 cfu/100mL (*E. coli*)
$\%POP_{2020-2070}$ = Estimated percent increase in population between 2020 and 2070
$WWTF_{FP}$ = Full permitted discharge (MGD)
Conversion Factor = 1.54723 cfs/MGD × 28,316.8 mL/ft^3 × 86,400 seconds/day ÷ 1×10^9

For Hillebrandt Bayou, the conventional FG calculations are hampered by the $WWTF_{FP}$ being zero. However, the TMDL must still account for the possibility of FG for the impaired AU. In order to address this shortcoming, an FG term was calculated for the Hillebrandt Bayou AU 0704_02 watershed. Currently, the Hillebrandt WWTF is located in the AU watershed but the outfall is located downstream of the TMDL watershed. The FG term was estimated as the percent population increase multiplied by the current permitted flow, with the assumption that the additional flow could be discharged within the TMDL watershed. The load allocation from the additional FG flow was calculated as described in Eq. 11 and shown in Table 18.

Table 18. Future growth calculation attributed to potential additional WWTF service in Hillebrandt Bayou AU 0704_02 watershed

AU	Current Permitted Flow (MGD)	Percent Increase	FG Flow (MGD)	FG (billion cfu/day)
0704_02	46	39.5	18.17	86.664

4.7.5. Load Allocation

The LA is the load from unregulated sources and is calculated as

$$\mathrm{LA} = \mathrm{TMDL} - \mathrm{WLA} - \mathrm{FG} - \mathrm{MOS} \tag{Eq.14}$$

Where:

LA = allowable load from unregulated sources within the AU
TMDL = total maximum daily load
WLA = sum of all WWTF loads and all regulated stormwater loads
FG = sum of future growth loads from potential regulated facilities
MOS = margin of safety load

Table 19 summarizes the LA calculations.

Table 19. Load allocation summary for Hillebrandt Bayou 0704_02 watershed

AU	TMDL†	WLA†	FG†	MOS†	LA†
0704_02	2,101.907	1,856.664	86.664	105.095	53.484

† in units of a billion cfu/day *E. coli*

4.8. Summary of TMDL Calculations

Table 20 summarizes the TMDL calculations for the project watershed. The TMDL was calculated based on median flow in the 0-10 percentile range (five percent exceedance, high flow regime) for flow exceedance from the LDC developed for SWQM station 10687. Allocations are based on the current geometric mean criterion for *E. coli* of 126 cfu/100mL for each component of the TMDL.

Table 20. TMDL allocation summary for Hillebrandt Bayou 0704_02 watershed

AU	TMDL†	MOS†	$\mathrm{WLA}_{\mathrm{WWTF}}$†	$\mathrm{WLA}_{\mathrm{SW}}$†	LA†	FG†
0704_02	2,101.907	105.095	0	1,856.664	53.484	86.664

† in units of a billion cfu/day *E. coli*

The final TMDL allocations (Table 21) needed to comply with the requirements of 40 CFR §103.7 include the FG component within the $\mathrm{WLA}_{\mathrm{WWTF}}$.

Table 21. Final TMDL allocations for Hillebrandt Bayou 0704_02 watershed

AU	TMDL†	WLA_{WWTF}†	WLA_{SW}†	LA†	MOS†
0704_02	2,101.907	86.664	1,856.664	53.484	105.095

† in units of a billion cfu/day *E. coli*

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Appendix A. DAR Parameter Estimation and Daily Streamflow Development

The DAR approach provides reliable estimates of mean daily streamflows in ungaged watersheds (Asquith et al., 2006; Hirsch, 1979; Ries and Friez, 2000). Asquith et al. (2006) recommend the source stream be located within 100 miles of the location of interest. The DAR approach also relies on similar land cover, hydrology, and other watershed characteristics. Streamflow estimation in Hillebrandt Bayou poses a challenge because nearby gages are primarily undeveloped or rural, while Hillebrandt Bayou is predominately developed (69.56 percent according to the 2016 NLCD data).

To overcome the available streamflow data limitations, DAR methods used by Asquith et al. (2006) and University of Houston (2018) were adapted with a flow duration curve transfer procedure (Linhart et al., 2012). This resulted in a two-step process to develop the daily streamflow for Hillebrandt Bayou:

1. Parameter estimation using watersheds with specific land cover characteristics; and
2. Daily stream flow development using nearby watersheds with similar precipitation characteristics.

Asquith et al. (2006) provide empirically derived parameter estimates for the DAR at different streamflow percentiles in order to address the tendency for the DAR method under- and over-estimating streamflows at high and low streamflow exceedance percentiles.

Parameter Estimation Using Watersheds with Specific Land Cover Characteristics

The University of Houston (2018) used a parameter estimation procedure to account for differences in developed areas and wetlands in the source watershed and the watershed of interest when applying the DAR. This procedure modifies the DAR with the following terms:

$$Y_p = X_p \times \left(\frac{A_y}{A_x}\right)^{\phi} \times \left(\frac{D_y}{D_x}\right)^{\Psi} \times \left(\frac{W_y}{W_x}\right)^{\Omega} \tag{Eq.15}$$

Where:

Y_p = streamflow for the ungaged location at streamflow percentile p,

X_p = streamflow for the gaged location at streamflow percentile p,

A_y = drainage area for the ungaged location,

A_x = drainage area for the gaged location,

D_y = developed area for the ungaged location,

D_x = developed area for the gaged location,

W_y = wetland area for the ungaged location,

W_x = wetland area for the gaged location,

ϕ, Ψ, Ω = estimated parameters.

Model parameters are estimated using naturalized streamflow data at two gaged stations, comparing the model output to the known streamflow and iteratively adjusting parameters until the error is minimized. This approach was modified to estimate only Ψ and Ω. Values of ϕ were used from the empirical estimates provided in Asquith et al. (2006).

In order to estimate Ψ and Ω, two USGS gaged watersheds within close proximity of each other and with different land cover characteristics were chosen. The Sims Bayou (USGS 08075400) and Chocolate Bayou (USGS 0807800) watersheds were used for parameter estimation (Table A-1, Figure A-1). The Sims Bayou watershed represents a small highly developed watershed. The Chocolate Bayou watershed is a slightly larger watershed approximately 11.5 miles from the Sims Bayou watershed with a higher proportion of rural land covers and wetlands. The daily flows (01/01/2006 through 12/31/2016) from the USGS gage were naturalized by subtracting the mean daily discharges reported in the DMR reports for permitted outfalls within each watershed. Reported diversions in both watersheds were either non-existent or minor (between 0 and 0.9 cfs per year) and not included in the naturalized flow adjustments used for parameter estimation.

Table A-1. Summary of watersheds used for parameter estimation procedure.

Watershed	**Total Area (acres)**	**Developed Area (acres)**	**Wetland Area (acres)**
Sims Bayou (USGS-08075400)	12,421.52	10,286.17	120.82
Chocolate Bayou (USGS-0807800)	54,574.55	9,299.92	5,150.28

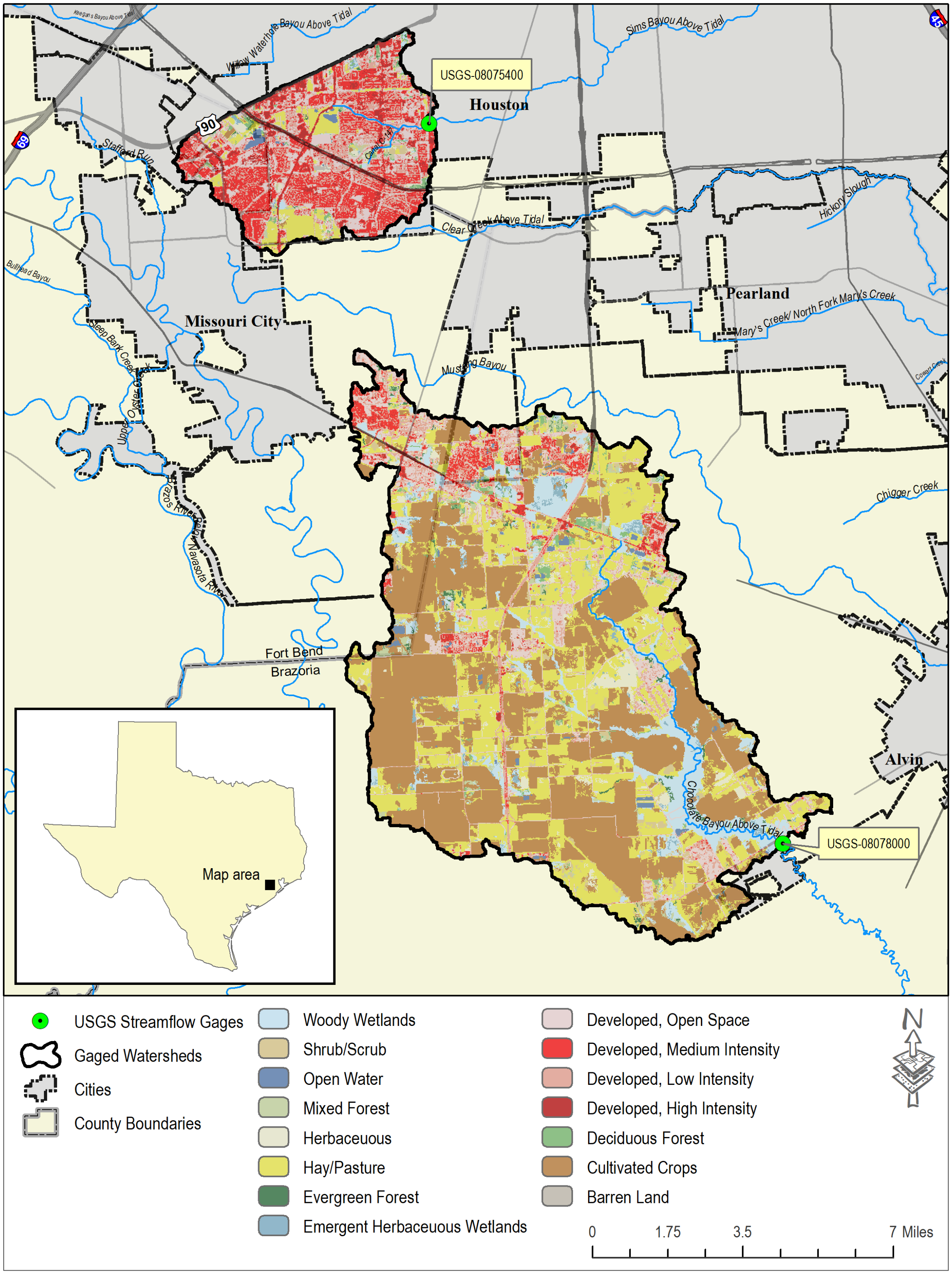

Figure A-1. Watershed locations and land cover used to develop parameters for DAR streamflow estimates. Sources: USGS Gage Locations (USGS, 2019b), National Land Cover Database (USGS, 2019a)

Parameter estimation was completed using a quasi-Newton optimization process to globally minimize the root mean square error (RMSE) between the predicted *Yp* and measured *Yp*. Optimization was completed using the "optim" function in program R.

The calculated parameter estimates are below:

- Ψ = 1.03037
- Ω = -0.0421

The goodness of fit was evaluated visually and using RMSE and Nash-Sutcliffe efficiency (NSE) between predicted *Yp* and measured *Yp* along the FDC (Figure A-2). The RMSE was 29.53 cfs and NSE was 0.96. This suggests very good model fit for values along the flow duration curve. Visual inspection indicates that predicted low flow values are biased below the observed flows with strong fit occurring at higher flows (Figure A-2). The downward bias at low flows is considered acceptable since the TMDL is calculated at the five percent exceedance flow, where the model fit is very strong.

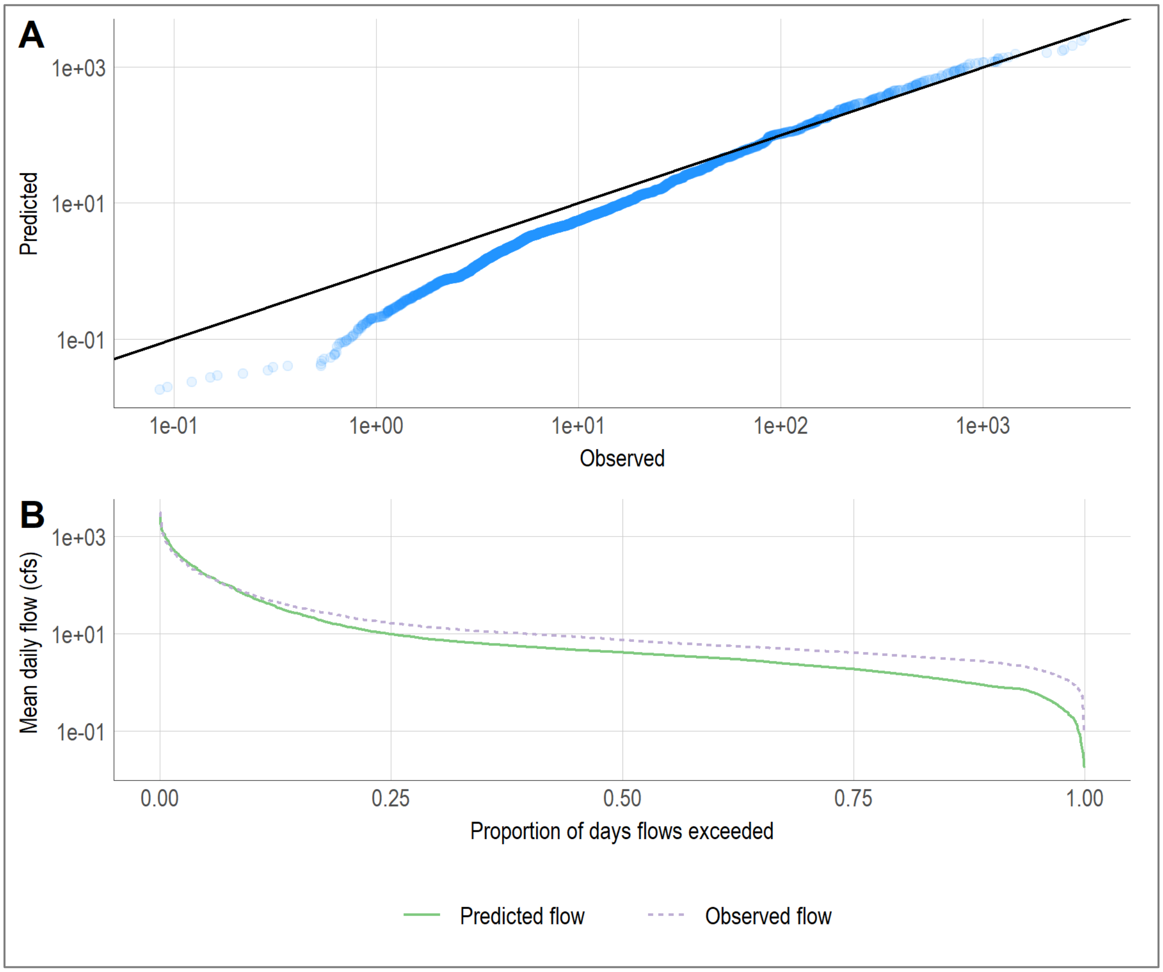

Figure A-2. (A) Visual inspection between observed and predicted values of *Yp* and (B) predicted and observed flow duration curve at Sims Bayou (USGS-08075400).

Daily Stream Flow Development Using Nearby Watersheds with Similar Precipitation Characteristics

After calculating parameters using known streamflows in Sims Bayou and Chocolate Bayou, the parameters can be plugged into the DAR equation to develop streamflows in Hilllebrandt Bayou using a nearby watershed. Streamflow estimation for Hillebrandt Bayou requires a nearby stream gage to provide daily streamflow estimates and calculate the proportion of days flow exceeded. The Cow Bayou (USGS-08031000) was selected to provide the daily mean streamflow record from 01/01/2005 through 12/31/2018 (Figure 11, Table A-2). The Cow Bayou watershed is approximately 17.6 miles from the Hillebrandt Bayou AU 0704_02 watershed, it is primarily rural, includes one permitted discharger, and has no water right diversions according to TCEQ water rights files. The naturalized streamflows at Cow Bayou were estimated by subtracting the average daily discharges reported in the DMR for the permitted discharger in the watershed. No further streamflow adjustments were necessary. Cow Bayou naturalized streamflows indicate zero streamflows approximately eight percent of the time. This is not anticipated to be reflective of Hillebrandt Bayou due to presence of streamflow during droughts in 2010 through 2011. Therefore, streamflows from the Menard Creek watershed (USGS gage 08066300, 01/01/2005 through 12/31/2018) were added to the calculation.

For a given streamflow percentile, each source stream will have a different flow due to difference in localized precipitation and runoff characteristics. Under these conditions, unless we know that the hydrology, precipitation, and runoff in one source stream is better representative than the other source stream, it is appropriate to apply the mean of estimated streamflows from both gaged locations as the streamflow in the area of interest as follows (Asquith et al., 2006).

$$Y_p = \frac{X_{1p} \times \left(\frac{A_y}{A_{x1}}\right)^{\Phi} \times \left(\frac{D_y}{D_{x1}}\right)^{\Psi} \times \left(\frac{W_y}{W_{x1}}\right)^{\Omega} + X_{2p} \times \left(\frac{A_y}{A_{x2}}\right)^{\Phi} \times \left(\frac{D_y}{D_{x2}}\right)^{\Psi} \times \left(\frac{W_y}{W_{x2}}\right)^{\Omega}}{2}$$

(Eq.16)

Where:

Yp = streamflow for the ungaged location at streamflow percentile p,

Xp = streamflow for the gaged locations *1* and *2* at streamflow percentile p,

A_y = drainage area for the ungaged location,

A_x = drainage area for the gaged locations *1* and *2*,

D_y = developed area for the ungaged location,

D_x = developed area for the gaged locations *1* and *2*,

W_y = wetland area for the ungaged location,

W_x = wetland area for the gaged locations *1* and *2*,

Φ = empirically estimated value from Asquith et al. (2006)

$\Psi = 1.03037$

$\Omega = -0.0421$

Table A-2. Summary of drainage areas used in DAR calculations.

Watershed	**Total Area (acres)**	**Developed Area (acres)**	**Wetland Area (acres)**
Cow Bayou (USGS-08031000)	56,894.89	3,653.44	20,869.15
Menard Creek (USGS-08066300)	94,389.04	5,234.85	13,522.87
Hillebrandt Bayou (SWQM-10687)	17,614.53	14,468.72	1,261.42

After the development of naturalized daily mean streamflow for each streamflow percentage *p* at Hillebrandt Bayou using the drainage area ratios from Cow Bayou and Menard Creek (Table A-2), the flow duration curve for Hillebrant Bayou is created. Since there are no additional permitted discharges or diversions upstream of the ungaged site, the flows did not require additional adjustment.

In order to construct the LDC at Hillebrandt Bayou, the daily streamflows must be reconstructed to match measured *E. coli* concentrations with estimated daily streamflows. By equating the exceedance probabilities at Cow Bayou (the nearest stream gage) and the ungaged site, the dates of streamflow associated with each exceedance probability at the reference stream gage are transferred to the ungaged site to construct a time series of streamflow at the ungaged site. Figure A-3 provides a visual outline of the basic transfer process as described in Linehart et al. (2012). The resulting FDC and daily streamflow estimate using this transfer procedure are displayed in Figure A-4.

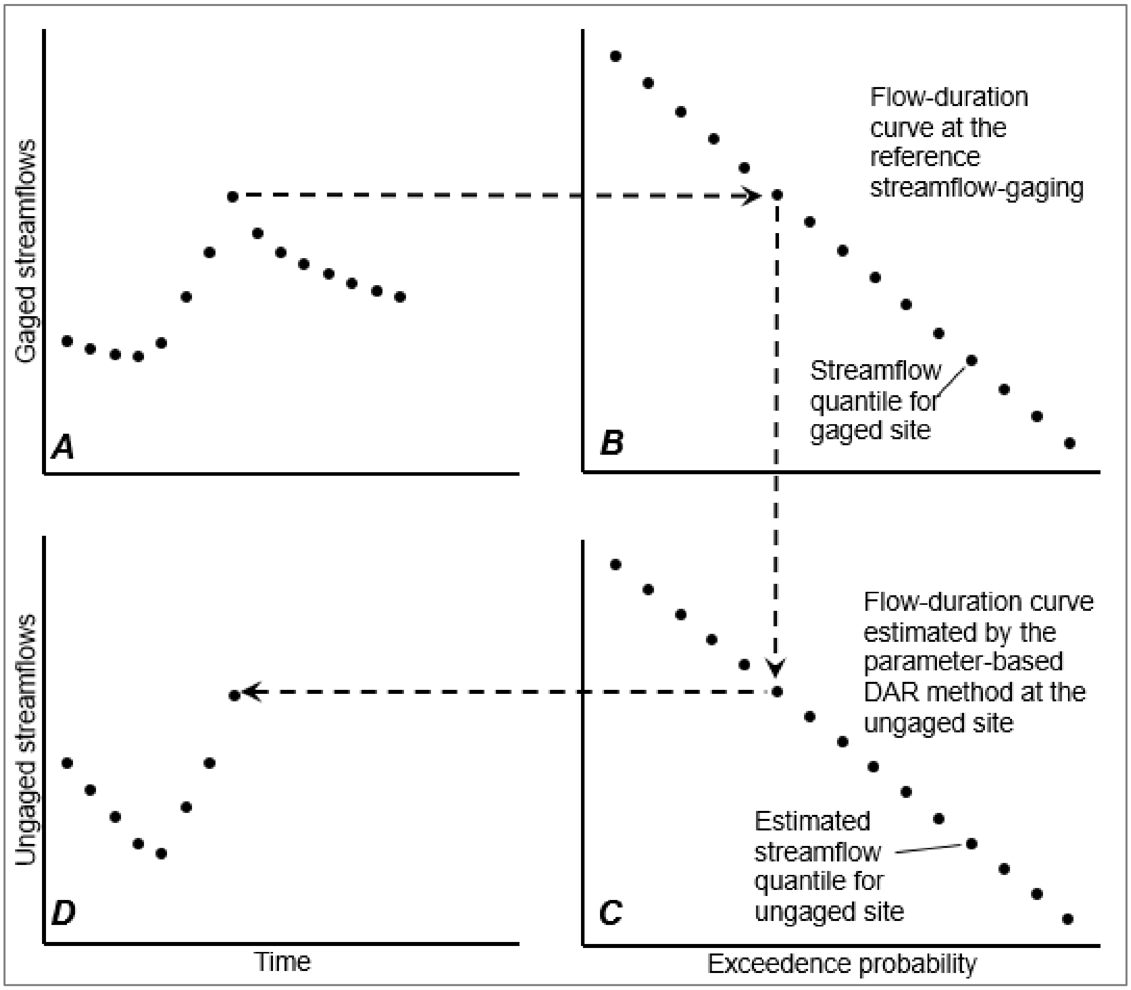

Figure A-3. Generalized process of transferring the FDC from source site to site of interest and to daily streamflows (Adapted from Linehart et al., 2012)

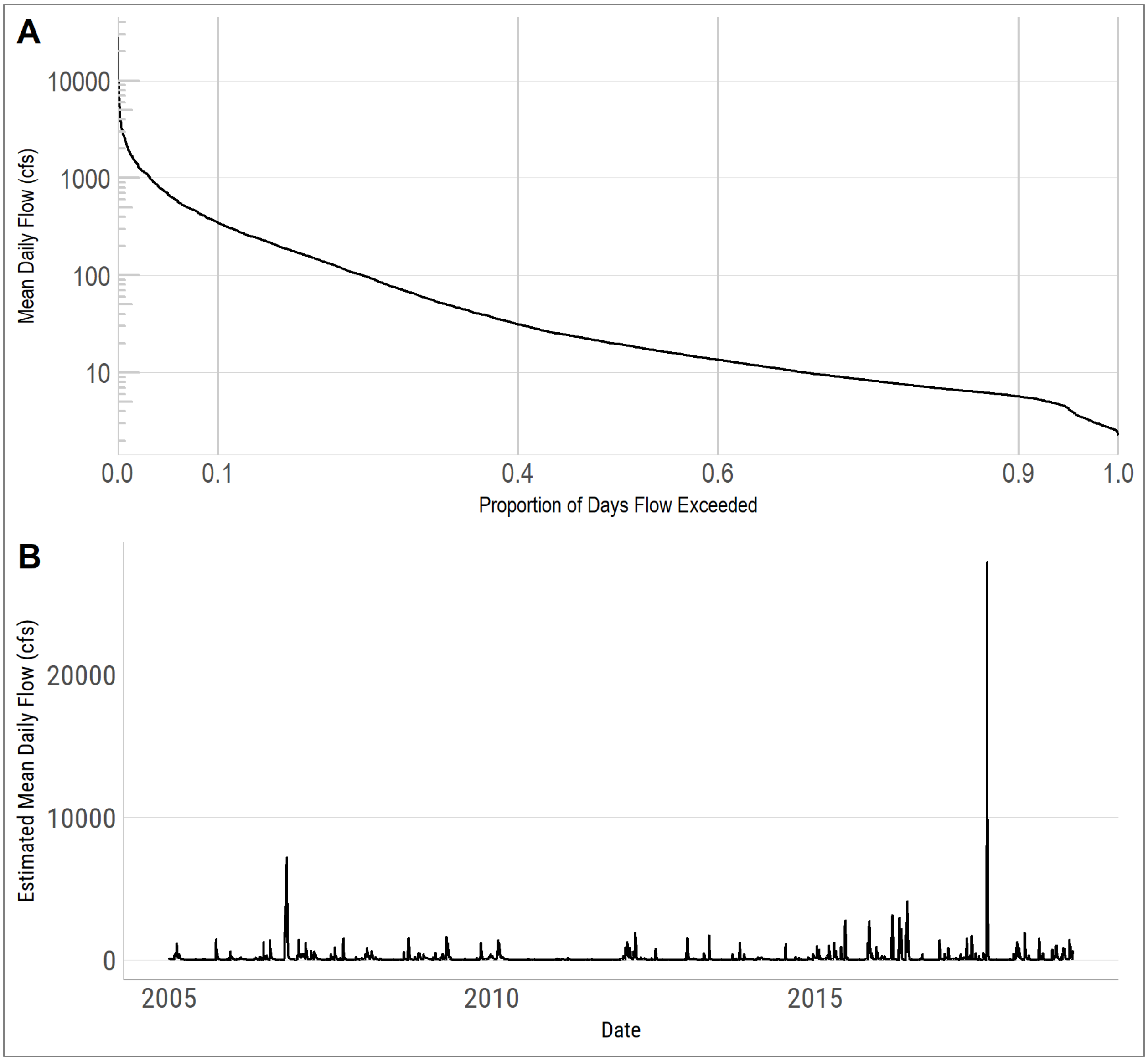

Figure A-4. (A) Flow duration curve in AU 0704_02 at station 10687 and (B) resulting estimated mean daily streamflow at station 10687 in AU 0704_02 from January 2005 through December 2018.