Technical Support Document for Total Maximum Daily Loads for Indicator Bacteria in the Navasota River Watershed

Segment 1209

Assessment Units: 1209_03, 1209_05, 1209E_01, 1209H_01, 1209H_02, 1209I_01, 1209J_01, 1209K_02

Prepared for
Total Maximum Daily Load Program
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Abbreviations and Acronyms

AU	Assessment Unit
AVMA	American Veterinary Medical Association
BRA	Brazos River Authority
CAFO	Concentrated Animal Feeding Operation
cfs	Cubic Feet per Second
DEM	Digital Elevation Model
ECHO	Enforcement & Compliance History Online
E. coli	*Escherichia coli*
ET	Evapotranspiration
FDC	Flow Duration Curve
FG	Future Growth
HRU	Hydrologic Response Unit
I&I	Inflow and infiltration
I-Plan	Implementation Plan
LA	Load Allocation
LDC	Load Duration Curve
MGD	Million Gallons per Day
mL	Milliliter
MOS	Margin of Safety
MPN	Most Probable Number
MSGP	Multi-Sector General Permit
MS4	Municipal Separate Storm Sewer System
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
OSSF	Onsite Sewage Facility
PET	Potential Evapotranspiration
SSO	Sanitary Sewer Overflow
SSURGO	Soil Survey Geographic Database
SUFI-2	Sequential Uncertainty Fitting 2
SWAT	Soil Water Assessment Tool
SWAT-CUP	Soil Water Assessment Tool- Calibration and Uncertainty Programs
SWQMIS	Surface Water Quality Monitoring Information System
TCEQ	Texas Commission on Environmental Quality
TMDL	Total Maximum Daily Load
TNRIS	Texas Natural Resources Information System
TPDES	Texas Pollutant Discharge Elimination System

TSSWCB	Texas State Soil and Water Conservation Board
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
WWTF	Wastewater Treatment Facility
95PPU	95% Prediction Uncertainty

SECTION 1

INTRODUCTION

1.1 Background

Section 303(d) of the federal Clean Water Act requires states to identify waters not meeting, or not expected to meet, applicable water quality standards. States must develop a Total Maximum Daily Load (TMDL) for each pollutant contributing to the listed water body impairment. The Texas Commission on Environmental Quality (TCEQ) is responsible for ensuring that NRISs are developed for impaired surface waters in Texas.

A TMDL is similar to a budget for a specific pollutant. It determines the maximum amount of a pollutant that the water body can receive and still meet applicable water quality standards. A TMDL represents the best estimate of a water body's assimilative capacity for specific pollutants. A TMDL is most often represented with units of mass per time period but can be expressed in other units when applicable. An implementation plan (I-Plan) is also developed with the TMDL. It is a framework of voluntary and regulatory strategies used to improve water quality after a TMDL is established.

TCEQ's TMDL Program is an essential component of the state's process for managing Texas' surface waters. The program addresses impaired or threatened streams, reservoirs, lakes, bays, and estuaries in, or bordering on, the state. Restoring and maintaining the beneficial uses of impaired or threatened water bodies including drinking water supply, recreation, support of aquatic life, or fishing is the primary objective of the TMDL Program.

Bacteria impairments were first identified in the Navasota River watershed in the 2002 Texas Water Quality and 303(d) List and have remained in subsequent versions. The *2016 Integrated Report – Texas 303(d) List* identified seven segments impaired in the Navasota River watershed due to *Escherichia coli (E. coli)*. Impaired water bodies include: the Navasota River below Lake Limestone (1209_03 and 1209_05), Wickson Creek (1209E_01), Duck Creek (1209H_01 and 1209H_02), Gibbons Creek (1209I_01), Shepherd Creek (1209J_01), and Steele Creek (1209K_02). Within this timeframe, several other water bodies were impaired due to elevated *E. coli* concentrations but were delisted through additional data collection.

Beginning in 2009, a recreational use attainability analysis was performed on impaired waterbodies in the Navasota River watershed to determine the appropriateness of the applied recreational water quality standards. Fieldwork performed and interviews conducted documented contact recreation in the lower portion of the Navasota River only. As such, a recommendation for a standards change to secondary contact 1 for the impaired tributaries has been made by TCEQ and is awaiting a decision by EPA.

In 2013, efforts to develop a watershed protection plan on the Navasota River downstream of Lake Limestone began. This plan outlines voluntary strategies to improve bacteria levels in waterbodies across the entire watershed. Collectively, these efforts will reduce bacteria contributions to waterbodies in all impaired and unimpaired portions of the watershed regardless of potential future standards changes or the presence of approved TMDLs.

This document will only focus on the impaired assessment units (AUs) listed previously.

1.2 Water Quality Standards

The Federal Clean Water Act delegated the authority and responsibility for developing and implementing water quality standards to the states. Under this authority and the Texas Water Code, TCEQ established water quality standards to safeguard public and environmental health while still promoting industry and economic development throughout the state. Water quality standards describe limits for water quality indicators that are monitored to assess the quality of water for specified uses. Monitoring and assessment is conducted by TCEQ based on established standards and results are published in the *Texas Water Quality Integrated Report* biennially.

The *Texas Surface Water Quality Standards* (TCEQ, 2010) 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 designated uses assigned to water bodies of which 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

In recreational waters, contamination from fecal bacteria and pathogens of warm-blooded animals are concerning since inadvertent ingestion may result in illness. Fecal indicator bacteria are used to assess the risk of water ingestion through contact recreation. *E. coli* and Enterococcus are present with many other microbes in the intestinal tracts of all endotherms. It is presumed, that the presence of these organisms in water signifies that pathogens also present in fecal matter may also be present. *E. coli* is the commonly used indicator organism in freshwater and Enterococci are preferred in high saline inland waters. *E. coli* is the relevant indicator organism for all water bodies in the Navasota River watershed.

On June 30, 2010, the TCEQ adopted revisions to the Texas Surface Water Quality Standards (TCEQ, 2010) and on June 29, 2011 the U.S. Environmental Protection Agency (EPA) approved the categorical levels of recreational use and their associated criteria. For freshwater, recreational use consists of three categories:

- Primary contact recreation is that with a significant risk of ingestion of water (e.g., wading by children, swimming, water skiing, diving, tubing, surfing, and the following whitewater activities: kayaking, canoeing, and rafting), and has a geometric mean criterion for *E. coli* of 126 per 100 mL;
- Secondary contact recreation 1 covers activities with limited body contact incidental to shoreline activity (e.g., wading by adults, fishing, canoeing, kayaking, rafting and motor boating). These activities are presumed to pose a less significant risk of water ingestion than primary contact

recreation but more than secondary contact recreation 2, and has a geometric mean criterion for *E. coli* of 630 per 100 mL;

- Secondary contact recreation 2 covers activities with limited body contact incidental to shoreline activity (e.g. fishing, canoeing, kayaking, rafting and motor boating) that are presumed to pose a less significant risk of water ingestion than secondary contact recreation 1. These activities occur less frequently than secondary contact recreation 1 due to physical characteristics of the water body or limited public access, and has a geometric mean criterion for *E. coli* of 1,060 per 100 mL;
- Noncontact recreation covers activities that do not involve a significant risk of water ingestion, such as those with limited body contact incidental to shoreline activity, including birding, hiking, and biking. Noncontact recreation use may also be assigned where primary and secondary contact recreation activities should not occur because of unsafe conditions, such as ship and barge traffic. It has a geometric mean criterion for *E. coli* of 2,060 per 100 mL.

Each impaired segment in the Navasota River watershed is currently designated for primary contact recreation (TCEQ 2014) and is not meeting the applied *E. coli* criterion of 126 MPN per 100 mL. Proposed water quality standards changes for the tributaries of the Navasota River may result in an *E. coli* criterion of 630 MPN per 100 mL being applied in the future. The Navasota River itself will remain categorized as a primary contact recreation water body.

1.3 Report Purpose and Organization

The TMDL Project on the Navasota River and its tributaries was initiated through a contract between the TCEQ and the Texas Water Resources Institute (TWRI). The purpose of this project was to collect watershed pollutant loading and instream water quality information for use in preparing a TMDL, I-Plan, and watershed protection plan. Historical data collected by TCEQ, the Brazos River Authority (BRA), and the U.S. Geological Survey (USGS) were paired with newly collected data to provide a complete dataset for us in developing loading estimates. Despite a robust data record in the watershed, limited water quality and streamflow information exists for some of the impaired tributaries. Therefore, the soil and water assessment tool (SWAT) was used to estimate flows in areas with deficient flow data.

Using this information, this technical support document intends to: review the characteristics of the watershed and describe potential sources of *E. coli* impacting the impaired segments; develop an appropriate tool for use in TMDL development; and submit supporting information for developing the bacteria TMDLs for the Navasota River watershed.

This report contains:

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

SECTION 2

WATERSHED OVERVIEW

2.1 Description of the Navasota River watershed

2.1.1 Description of Study Area

The Navasota Watershed is located in East-Central Texas and contains parts of eight counties including Brazos, Freestone, Grimes, Hill, Leon, Limestone, Madison, and Robertson. There are two reservoirs on the main stem of the Navasota River, thus the watershed is often divided into three primary segments: the Navasota River below Lake Limestone (1209), the Navasota River above Lake Mexia (1210A), and the Navasota River below Lake Mexia (1253) (Figure 1~~Figure 1~~).

Segment descriptions described in the *2014 Texas Integrated Report – Texas 303(d) List* are:

- Segment 1209 – Navasota River Below Lake Limestone: From the confluence with the Brazos River in Grimes County to Sterling C. Robertson Dam in Leon/Robertson County
- Segment 1210A – Navasota River above Lake Mexia: From the confluence with the headwaters of Lake Mexia in Limestone County to a point 1.25 miles upstream of SH 31 in Hill County
- Segment 1253 – Navasota River below Lake Mexia: From a point 2.3 km (1.4 miles) downstream of SH 164 in Limestone County to Bistone Dam in Limestone County

All impaired segments of the river and tributaries are located in the watershed downstream of Lake Limestone (Segment 1209). This segment of the Navasota River flows from the Sterling C. Robertson Dam that forms Lake Limestone, downstream to its confluence with the Brazos River south of State Highway 105 and West of the City of Navasota. The watershed for this area covers 1,006,330 acres of mostly rural landscapes and consists of grass pastures, hay fields, and hardwood forests in bottomland and upland areas. Urbanization is not widespread and occurs primarily in the Bryan/College Station area in Brazos County. The river is a perennial freshwater stream, but the operations of Lake Limestone are a strong influence on its flows. This area downstream of Lake Limestone will be the focus of this technical support document; however, graphics may include the upstream portion of the watershed to convey relevant information.

Within these segments, only two AUs of Segment 1209 are impaired for elevated *E. coli.* Additionally, six tributary AUs are impaired for elevated *E. coli.* Descriptions for these impaired AUs are:

- AU 1209_03: Portion of the Navasota River from confluence with Sandy Branch upstream to confluence with Shepherd Branch in Madison County
- AU 1209_05: Portion of the Navasota River from confluence with Camp Creek upstream to Lake Limestone Dam in Robertson County
- 1209E Wickson Creek – Entire water body: Perennial stream from the confluence with an unnamed first order tributary (approximately 1.3 km upstream of Reliance Road crossing) upstream to the confluence with an unnamed first order tributary approximately 15 meters upstream of Dilly Shaw Road

- 1209H Duck Creek – From the confluence with the Navasota River in Robertson County to Twin Oak Reservoir dam in Robertson County
    - AU 1209H_01 – Portion of Duck Creek from confluence with Navasota River upstream to confluence with Mineral Creek in Robertson County
    - AU 1209H_02 – Portion of Duck Creek from confluence with Mineral Creek in Robertson County upstream to headwaters in Limestone County
- 1209I Gibbons Creek – From confluence with Navasota River in Grimes County to SH 90 in Grimes County
    - AU 1209I_01 – Portion of Gibbons Creek from confluence with Navasota River upstream to confluence with Dry Creek in Grimes County
- 1209J Shepherd Creek – Entire water body: From the confluence with the Navasota River in Madison County to a point 0.7 miles upstream of FM 1452 in Madison County
- 1209K Steele Creek – From confluence with Navasota River in Robertson County to a point 2.4 miles upstream of FM 147 in Limestone County
    - AU 1209K_02 – Portion of Steele Creek from confluence with Willow Creek upstream to headwaters in Limestone County

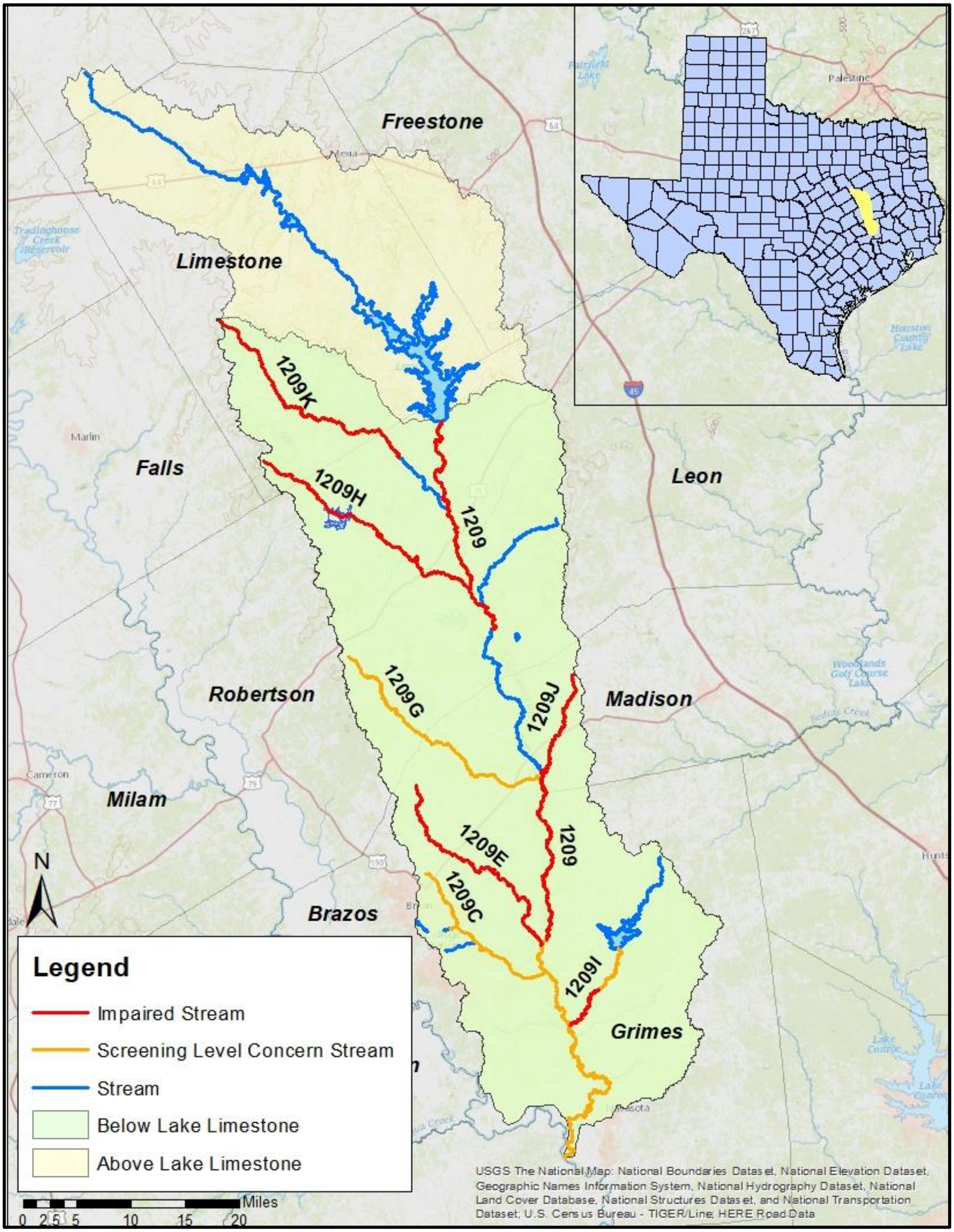

Figure 1. The Navasota watershed split into Above Lake Limestone and Below Lake Limestone.

2.1.2 Watershed Climate and Hydrology

The Navasota watershed is located in East-Central Texas and typically has hot, humid summers, and mild winters. Average annual temperatures in the watershed range from the mid-50s°F to approximately 80°F. Monthly average lows range from 35°F to 42°F and the average high is 96°F (Figure 2Figure 2).The watershed receives 34 to 44 inches of rainfall annually (Figure 3Figure 3).

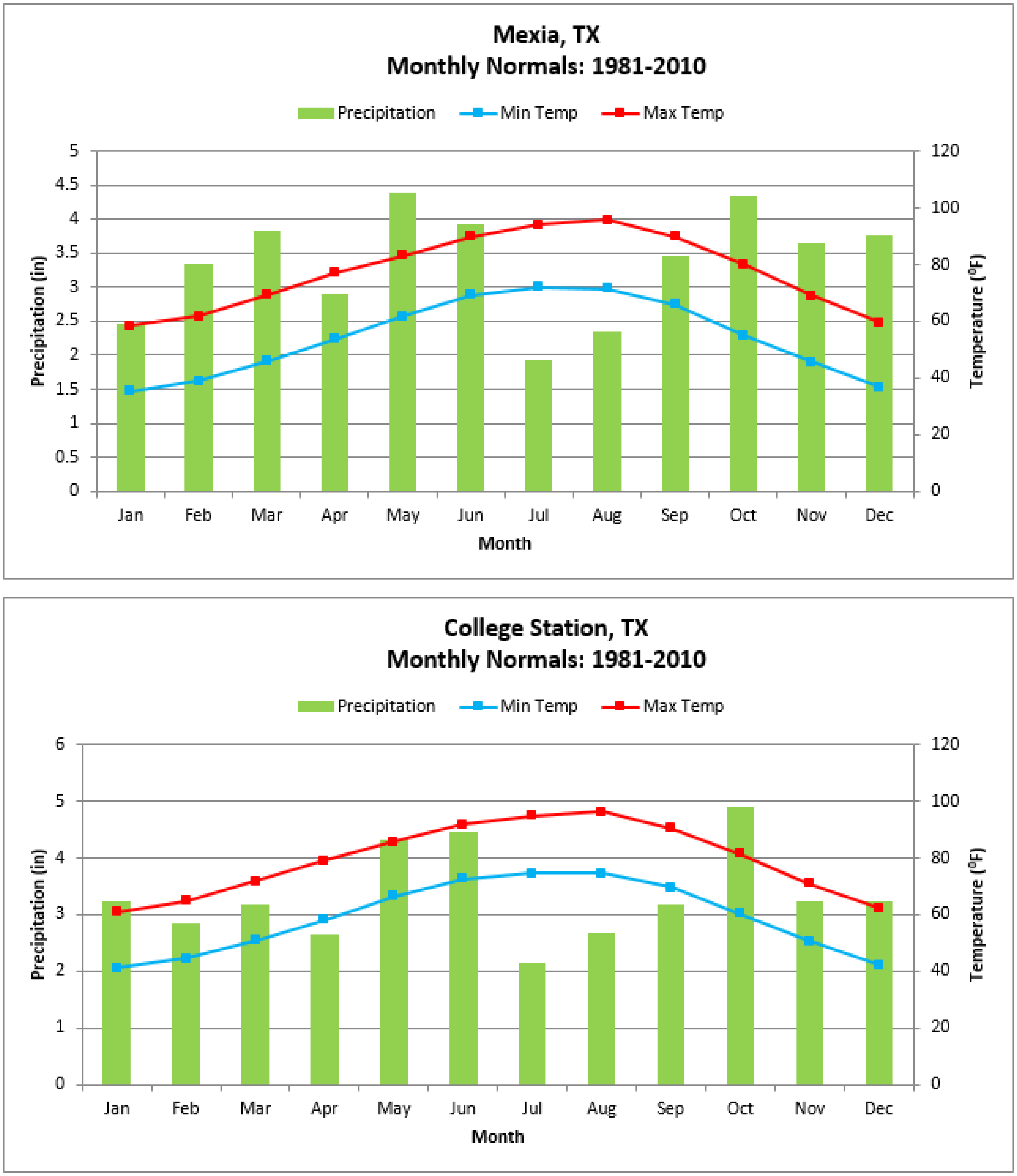

Figure 2. Average minimum and maximum air temperatures and total precipitation by month over 1981-2010 for the Mexia and College Station areas in the Navasota River watershed (NOAA, 2014).

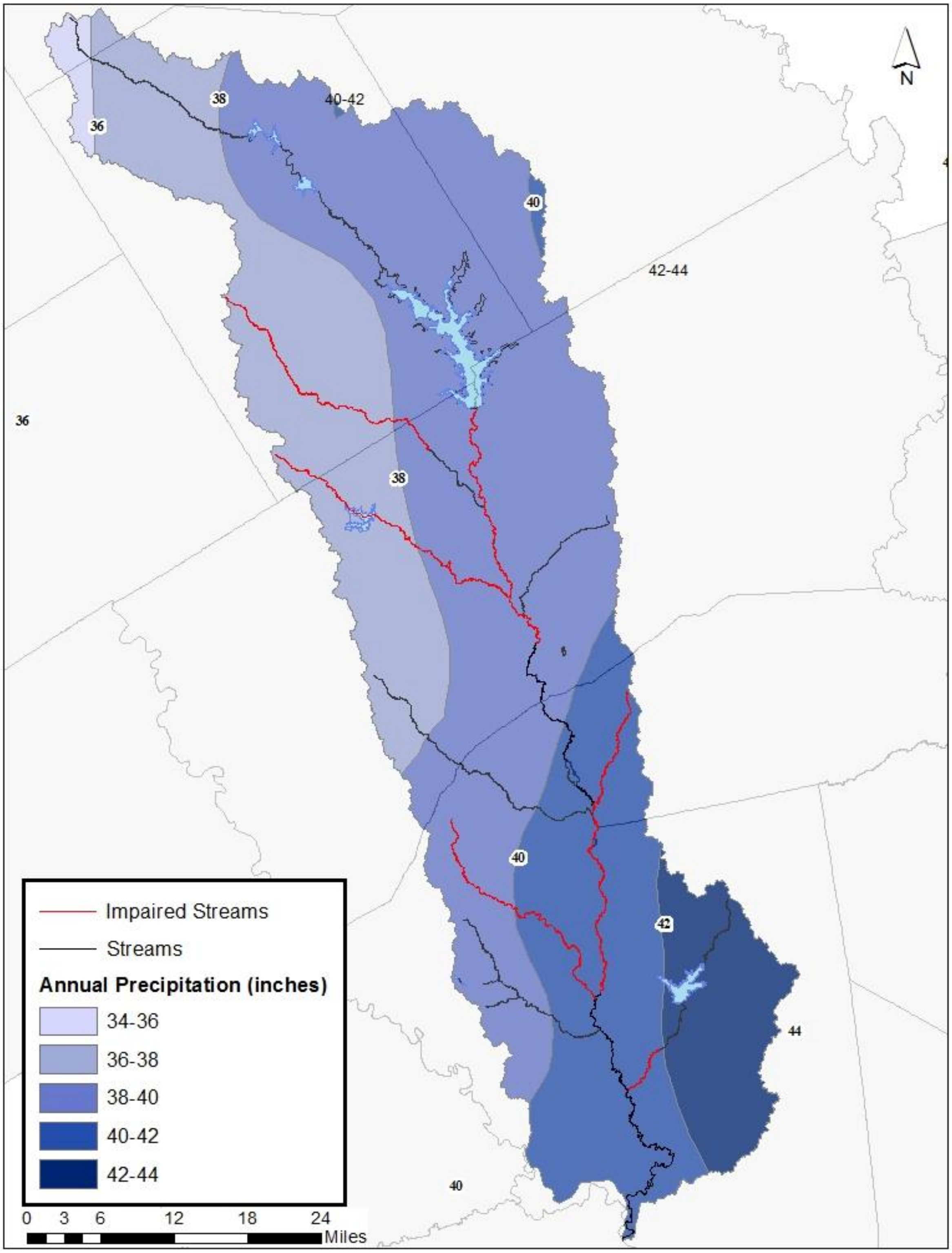

Figure 3. Annual average precipitation (inches) for the Navasota Watershed (TWDB 2014a).

The river above and below Lake Mexia (Segments 1210A and 1253) is characterized as a small prairie stream experiencing little to no flow frequently throughout the year (TCEQ 2010c). The Navasota River below Lake Limestone (Segment 1209) begins at the outfall of the Sterling C. Robertson Dam that was constructed in 1978 and continues downstream to its confluence with the Brazos River, west of the town of Navasota (Figure 1). The river traverses some of the few remaining bottomland hardwood habitats in the state. Segment 1209 is characterized by its narrow shape, with river banks ranging from relatively accessible to very steep and incised. A river maintenance release of 6 cfs from Lake Limestone, groundwater return flows, and wastewater inputs sustain the river's flow between storm events. Releases from Lake Limestone have a significant influence on instream water levels and flow rates, but are most commonly made following storm events. Periodically, water supply releases to downstream users are made. In the lower half of the watershed, the river lies in a large floodplain that frequently floods after large rainfalls and large releases from Lake Limestone.

Historical data available from USGS gaging stations indicates that in 1899, the flood of record was measured near present day US Hwy 79 and peaked at 90,000 cfs (Phillips, 2007). Downstream at Old San Antonio Road, the flood of record was measured in 2009 when the river crested at 54,300 cfs. The rural nature of the watershed naturally attenuates these floods by absorbing vast amounts of water before yielding runoff that produces a flood. The mixed forests, managed pastures, and rangelands covering the bulk of the watershed retain significant amounts of moisture, but their capacity is often exceeded during high intensity or large rain events. Much like a truly natural system functions, high flow conditions following a flood are typically extended as the watershed slowly releases stored moisture. Releases from Lake Limestone are capable of generating major flood conditions without the addition of rainfall runoff. The cities of Bryan and College Station produce the largest amount of stormwater runoff, which causes rapid rises and falls in local stream flow. Numerous tributaries of the Navasota River drain the watershed with 11 being assigned segment identification codes by TCEQ. Of these, four lie within the cities of Bryan and College Station while the other seven flow through rural areas. All 11 tributaries contribute water to the Navasota River below Lake Limestone (Figure 1).

2.1.3 Watershed Population and Population Predictions

The Navasota watershed is predominantly rural, with the majority of urban development centered around the cities of Bryan and College Station (Table 4~~Table 4~~). Approximately 83% of the watershed population is estimated to reside in the Bryan and College Station area. Population estimates from the 2010 census for the portion of each county in the watershed range from 1,419 in Madison County to 156,941 in Brazos County (Table 1~~Table 1~~). Significant population growth is anticipated to occur over the next 50 years (Table 2~~Table 2~~). Combining estimates for each county, growth is expected to increase 102% by 2070.

Table 1. Population and population density in the watershed.

County	County Population in Watershed	Population Density Per Square Mile	Projected 50 year Percent (entire county)
Brazos	156,941	376.5	124 %
Grimes	11,170	34.5	48 %
Madison	1,419	20.2	44 %
Leon	5,235	21.3	47 %
Limestone	1,735	11.5	34 %
Robertson	4,540	12.4	62 %

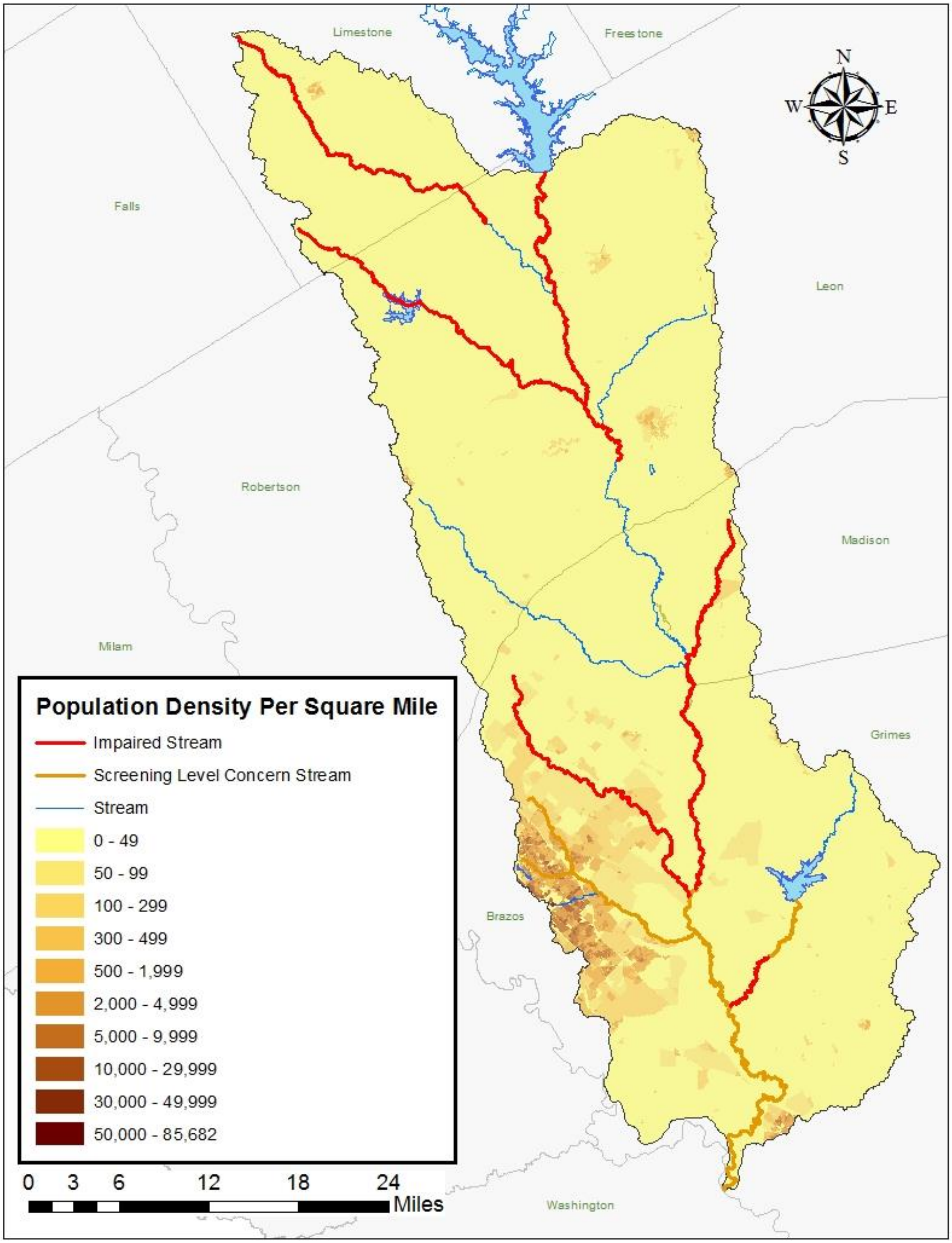

Figure 4. Population density per square mile in the Navasota watershed.

Table 2. 2010 Population Census Statistics and Population Projections for the counties within the watershed (TWDB 2014b; U.S. Census Bureau 2010).

County	2010 U.S. Census	2020 Population Projection	2030 Population Projection	2040 Population Projection	2050 Population Projection	2060 Population Projection	2070 Population Projection	Percent Increase (2010-2070)
Brazos	203,164	227,654	264,665	302,997	349,894	400,135	455,529	124%
Grimes	26,859	29,441	32,179	34,258	36,454	38,277	39,867	48%
Madison	13,781	14,753	15,817	16,786	17,872	18,886	19,877	44%
Leon	16,742	18,211	19,536	20,603	22,071	23,340	24,582	47%
Limestone	23,326	25,136	26,615	27,817	29,134	30,206	31,152	34%
Robertson	16,486	18,358	20,150	21,801	23,525	25,174	26,771	62%
Total	300,358	333,553	378,962	424,262	478,950	536,018	597,778	

2.2 Review of Navasota River Watershed Routine Monitoring Data

2.2.1 Data Acquisition

Water quality monitoring has occurred at 29 different locations throughout the Navasota River watershed at various points in time; however, many of those sites were only active for a short time during a special project, or were moved due to changes in hydrologic conditions. For this report, water quality data from TCEQ Surface Water Quality Monitoring Information System (SWQMIS) was accessed on June 23, 2016. Only data from monitoring stations on impaired water bodies used for assessment purposes in the 2014 Texas Integrated Report were accessed. This approach included data from routine Clean Rivers Program monitoring efforts conducted by the Brazos River Authority and from a special project conducted by TWRI.

2.2.2 Analysis of Bacteria Data

The period of record evaluated coincides with the date range for the water quality assessment conducted to produce the 2014 Texas Integrated Report: December 1, 2005 - November 30, 2012. During this time, water quality monitoring was conducted at 24 stations; however, a number of these stations are no longer monitored. The Navasota River and the tributaries must currently meet water quality standards and maintain *E. coli* levels at or below a geometric mean of 126cfu/100mL for primary contact recreation. Since *E. coli* is a fecal indicator bacteria for other pathogens as such it can be used as a protective measure for human health. If *E. coli* levels are found to exceed their standard limits, the probability of contracting gastrointestinal illnesses is expected to increase.

The active water quality monitoring initiated by TCEQ allows for a more accurate representation of the water quality based on streamflow conditions. The TCEQ published the geometric mean of their assessed samples in the 2014 Texas Integrated Report. Those values are summarized in Table 3~~Table 3~~. These values exceed the 126 cfu/100 mL standard for recreational use. According to the 2014 Texas Integrated Report, waterbodies in the study area that are impaired for *E.coli* include the Navasota River below Lake Limestone (Segment 1209_03 & 05), Carter's Creek (Segment 1209C), Country Club Branch (Segment 1209D), Wickson Creek (Segment 1209E), Duck Creek (Segment 1209H_01 & 02), Gibbons Creek (Segment 1209I), Shepherd Creek (Segment 1209J), Steele Creek (Segment 1209K_02), Burton

Creek (Segment 1209L) and the Navasota River above Lake Mexia (Segment 1210A) (Figure 5~~Figure 5~~). Carters Creek, Burton Creek, and Country Club Branch have a completed TMDL and the Navasota River above Lake Mexia is recommended for a water quality standards change. These segments are not considered in the assessment for this technical support document.

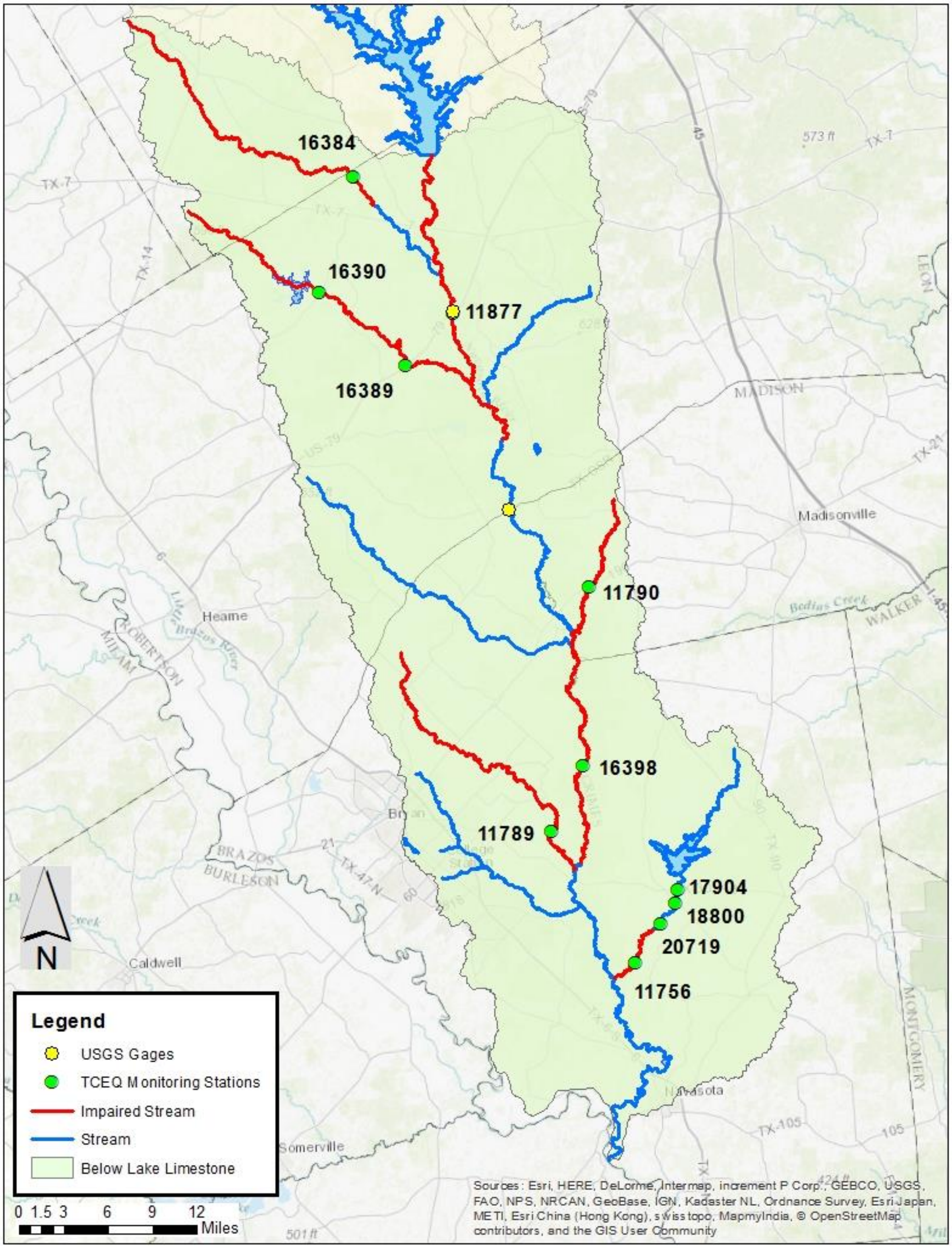

Figure 5. The location of the USGS gages and TCEQ monitoring sites and the monitoring sites providing data for this assessment.

Table 3. Navasota River and tributary segments impaired due to elevated *E. coli*.

AUID	Water Body Name	Data Date Range	Stations	No. Samples	2014 Texas IR Geometric Mean
1209_03	Portion of Navasota River from confluence with Sandy Branch upstream to confluence with Shepherd Branch in Madison County	Sept 2001 – Feb 2010	**16398**	57	91.35
1209_05	Portion of Navasota River from confluence with Camp Creek upstream to Lake Limestone Dam in Robertson County	Jan 2001 – Feb 2016	11877	91	148.59
1209E_01	Wickson Creek	Sept 2001 – Aug 2007	**11789, 15033**	27	313.66
1209H_01	Duck Creek	Sept 2001 – July 2012	**16389**	55	397.77
1209H_02	Duck Creek	Sept 2001 – Aug 2007	**16390**	36	317.13
1209I_01	Gibbons Creek	Sept 2011 – July 2011	**11756**	50	168.27
1209I_02	Gibbons Creek	Feb 2007 – May 2015	**17904,** 18800, **20719**	32	137.16
1209J_01	Shepherd Creek	Oct 2009 – March 2011	**11790**	12	426.85
1209K_02	Steele Creek	Sept 2009 – Aug 2011	**16384**	24	218.4

*Bold stations are not actively monitored

2.3 Land Use

The land use/land cover data for the Navasota watershed was obtained from the U.S. Geological Survey 2011 National Land Cover Database (NLCD) (Figure 6~~Figure 6~~). Land use/land cover is represented by the following categories and definitions (USGS, 2014):

- *Open Water - areas of open water, generally with less than 25% 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% of total cover. These areas most commonly include large-lot single-family 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% 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% to 79% of the 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% to 100% of the 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% of total cover.*
- *Deciduous Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.*

- *Evergreen Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.*
- *Mixed Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.*
- *Shrub/Scrub - areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.*
- *Grassland/Herbaceous - areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% 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% of total vegetation.*
- *Cultivated Crops - areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.*
- *Woody Wetlands - areas where forest or shrubland vegetation accounts for greater than 20% 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% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.*

Land use / land cover for the watershed is divided according to the NLCD map classifications. Most of the land in the Navasota watershed is hay/pasture land (37.9%) or forested land (24.8%) as displayed in Table 4Table 4. There is limited cultivated crop production. Crop data from the United States Department of Agriculture (USDA) suggested that minimal corn and cotton production occur in isolated areas within the southern portion of the watershed. The only large concentration of developed land within the watershed is representative of the cities of Bryan and College Station in the southeastern portion of the watershed.

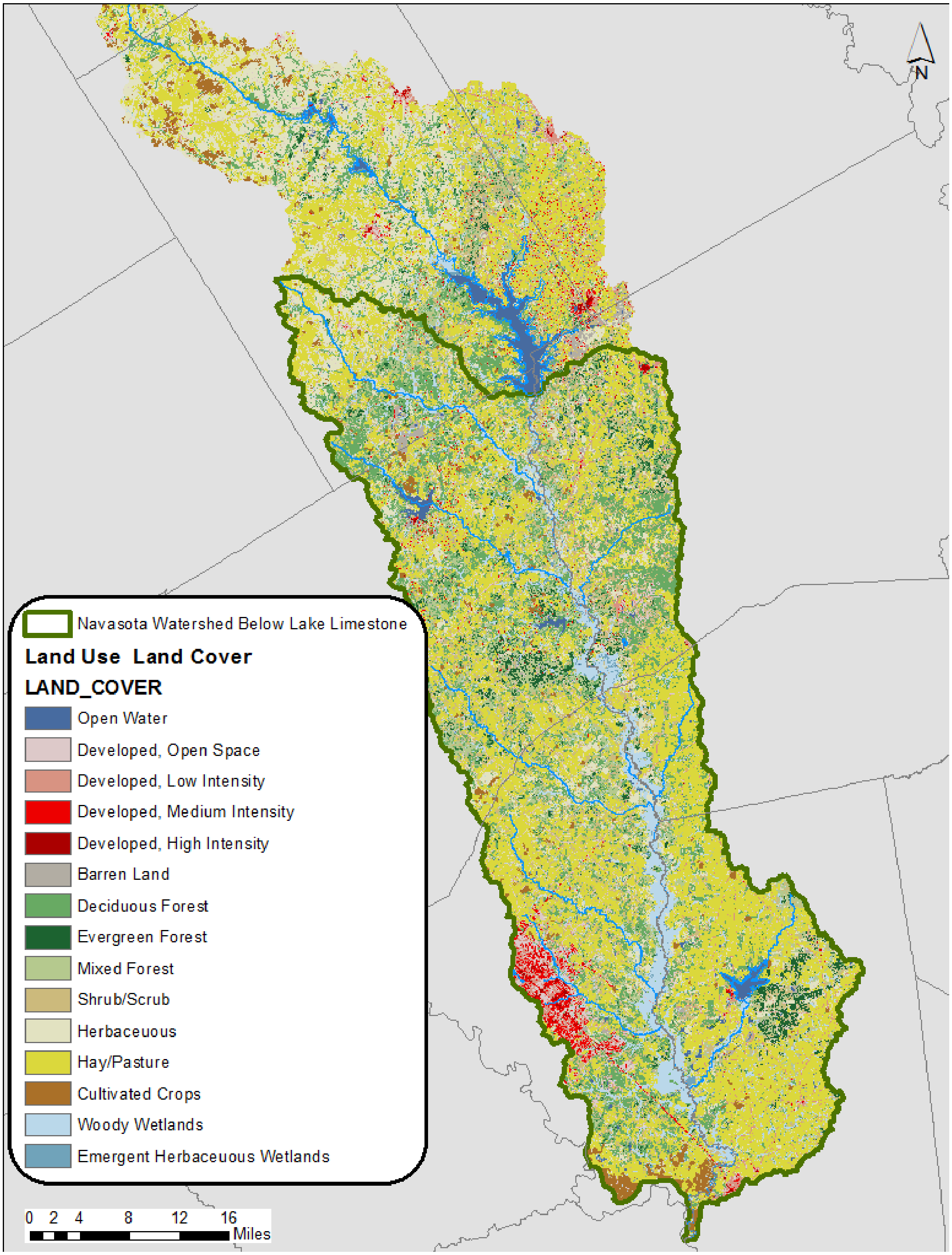

Figure 6. 2011 NLCD Land use/land cover within the Navasota Watershed.

Table 4. Land Use/land cover in the Navasota River watershed.

	Sub-watershed	1	2	3	4	5	6	7	8	9	10	11	12	13	Acres of Category Watershed	Percent of Category Watershed
Developed	**Acres**	5,297	6,732	5,077	4,149	5,451	2,916	784	3,005	3,605	20,987	4,361	7,789	7,215	**77,367**	**7.7**
	%	4.46	6.21	5.27	5.65	5.59	3.78	4.69	4.01	6.39	48.16	5.76	14.9	6.26		
Barren Land	**Acres**	2,251	2,711	1,322	979	297	373	27	39	36	80	633	568	202	**9,517**	**0.9**
	%	1.9	2.5	1.37	1.33	0.3	0.48	0.16	0.05	0.06	0.18	0.84	1.09	0.17		
Shrub/Scrub	**Acres**	8,223	15,340	8,522	8,489	10,318	10,073	965	6,094	5,866	2,946	5,584	4,125	6,526	**93,072**	**9.2**
	%	6.93	14.16	8.85	11.56	10.58	13.06	5.78	8.14	10.4	6.76	7.37	7.89	5.66		
Herbaceous	**Acres**	19,904	9,931	7,204	6,933	7,358	8,187	143	6,142	3,443	1,281	4,703	2,206	3,683	**81,117**	**8.1**
	%	16.77	9.17	7.48	9.45	7.54	10.61	0.86	8.2	6.1	2.94	6.21	4.22	3.19		
Hay/Pasture	**Acres**	37,941	37,025	32,804	16,968	33,969	28,436	11,844	32,233	29,734	6,669	35,761	15,307	63,037	**381,727**	**37.9**
	%	31.96	34.17	34.07	23.12	34.83	36.86	70.88	43.04	52.72	15.3	47.2	29.29	54.67		
Cultivated Crops	**Acres**	2,654	659	2,336	669	412	1,113	0	704	1,026	253	409	35	8,953	**19,222**	**1.9**
	%	2.24	0.61	2.43	0.91	0.42	1.44	0	0.94	1.82	0.58	0.54	0.07	7.77		
Forest	**Acres**	32,891	29,978	31,703	29,961	24,555	22,162	2,081	13,684	10,374	6,483	17,390	13,354	14,932	**249,547**	**24.8**
	%	27.7	27.67	32.93	40.82	25.17	28.73	12.45	18.27	18.39	14.88	22.95	25.55	12.95		
Wetlands	**Acres**	9,218	5,325	5,132	4,137	14,448	3,716	793	12,614	2,110	4,718	3,538	8,106	9,916	**83,773**	**8.3**
	%	7.76	4.91	5.33	5.64	14.81	4.82	4.75	16.84	3.74	10.83	4.67	15.51	8.6		
Open Water	**Acres**	344	641	2,176	1,119	730	174	73	378	208	159	3,383	770	834	**10,987**	**1.1**
	%	0.29	0.59	2.26	1.52	0.75	0.23	0.43	0.5	0.37	0.36	4.47	1.47	0.72		
Total Acres	**Acres**	118,722	108,342	96,276	73,405	97,538	77,150	16,710	74,893	56,402	43,577	75,764	52,260	115,297	**1,006,329**	
Percent of Watershed	**%**	11.8	10.77	9.57	7.29	9.69	7.67	1.66	7.44	5.6	4.33	7.53	5.19	11.46		

Developed: Medium, Low, and High Intensity are aggregated into a single Developed category. Similarly, multiple forest types and wetland types have been generalized into single classes (NLCD 2011).

2.4 Soils

According to data retrieved from the USDA Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (NRCS, 2013), soils categorized in three Hydrologic Soil Groups can be found in the watershed, and are shown in Figure 7Figure 7. Soils in Group B are typically silt loams or loams with a moderate infiltration rate when thoroughly wet. Soils in this group cover approximately 32% of the watershed area. Hydrologic Group C soils are sandy clay loams that have low infiltration rates when wet and generally have a less permeable layer that impedes downward water movement. These soils cover approximately 11% of the watershed area. Soils in Group D have the highest runoff potential, and the lowest infiltration rate. Most soils in this group shrink and swell as moisture conditions change. Approximately 56% of the watershed is made up of soils in this group.

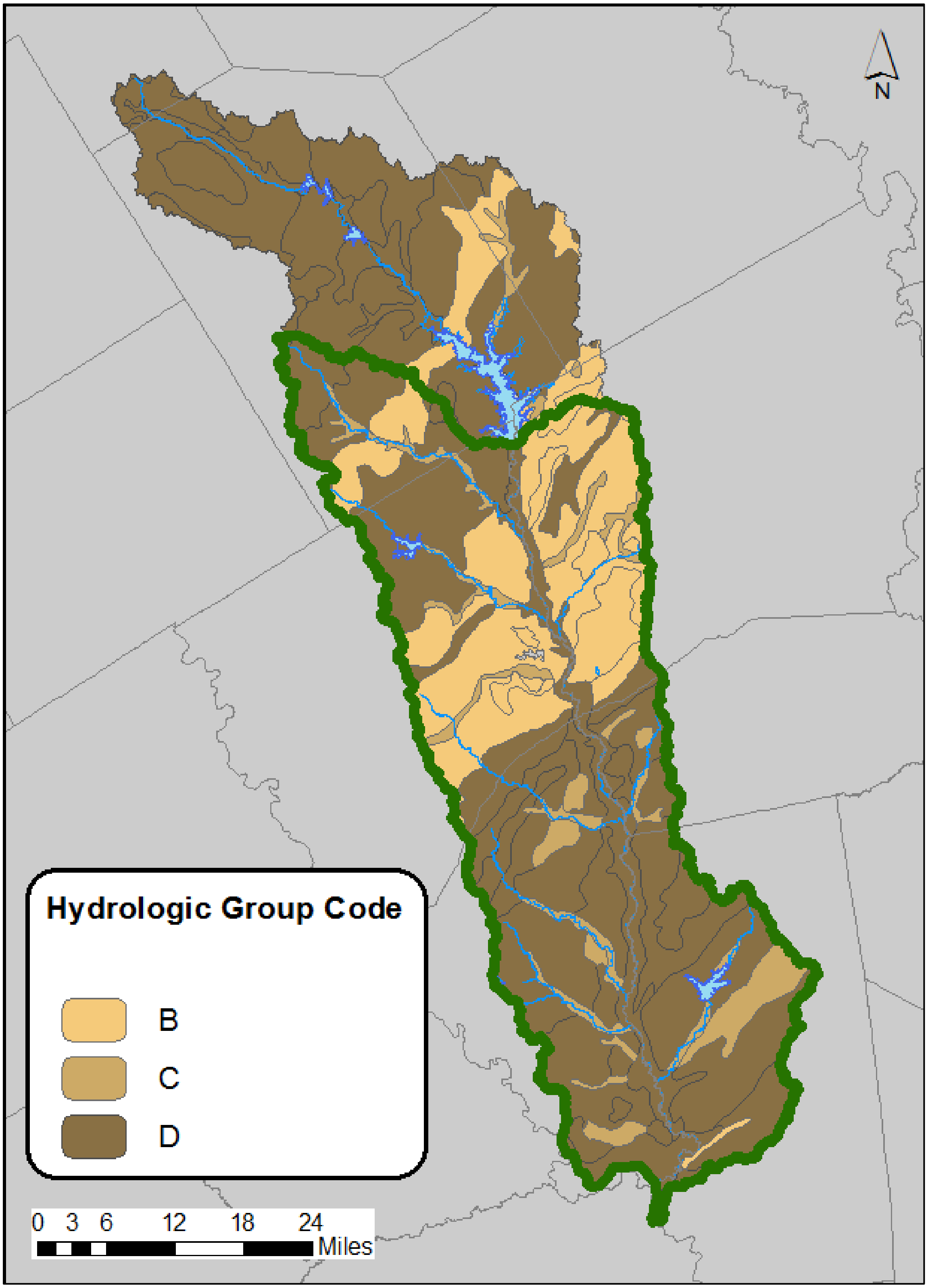

Figure 7. Hydrologic Soil Groups for the Navasota Watershed.

2.5 Potential Sources of Fecal Indicator Bacteria

Potential indicator bacteria pollution sources can be 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. Examples of regulated pollutant sources include wastewater treatment facility (WWTF) discharges and stormwater discharges from industries, construction, and municipal separate storm sewer systems (MS4s) of cities.

Unregulated sources are generally nonpoint sources meaning that the pollution originates from multiple locations across a watershed and is usually carried to surface waters by rainfall runoff. Nonpoint sources are not regulated by permit.

The regulated and unregulated sources in this section are presented to give a general account of the potential sources of bacteria within the watershed.

2.5.1 Permitted Sources

Fecal indicator bacteria from regulated sources can come from WWTFs, processing water and stormwater runoff discharges from urban, industrial, and select agricultural areas. TCEQ requires permits for point source discharges. As of February 2017, there are 21 TPDES/NPDES permits for facilities in the watershed downstream of Lake Limestone (Table 5~~Table 5~~). These include wastewater permits, cooling water discharge permits, industrial discharges, and mine dewatering discharge permits and are measured as million gallons per day (MGD).

2.5.1.1 TPDES General Permits

TPDES General Permits include construction general permits, municipal separate storm sewer systems (MS4), concrete production plant general permits, wastewater evaporation pond permits and concentrated animal feeding operation (CAFO) general permits. The permits within the watershed include:

- TXG110000 – concrete production facilities
- TXG92000 – concentrated animal feeding operations
- WQG100000 – wastewater evaporation ponds

Eleven facilities within the watershed discharge treated domestic wastewater. These facilities are in: Brazos (6), Grimes (2), Leon (2), and Limestone (1) counties. Other permitted facilities in the watershed include a feed mill, a confined animal feeding operation (CAFO), industrial facilities, cooling water dischargers, and mining dewatering operations. WWTFs treat domestic wastewater and generally discharge limited amounts of *E. coli.* Similarly, if CAFOs operate according to their permit, no discharge to water bodies occurs. However, failures sometimes occur in both CAFOs and WWTFs and result in unplanned releases of wastewater and associated *E. coli.* Cooling water and industrial facilities do not provide a significant source of *E. coli* to the watershed.

Table 5. Permitted point sources discharge facilities in the Navasota River Watershed.

TPDES Permit No.	NPDES No.	Facility	Receiving Waters	Final Permitted Discharges (MGD)[a]	Recent Discharge (MGD)
N/A	TX0108863	ARKEMA INC	N/A	*	*
WQ0013931001	TX0116378	CITY OF ANDERSON: WWTF	To an unnamed tributary, thence to Holland Creek and to the Navasota River Below Lake Limestone in Segment 1209 of the Brazos River Basin	0.065	0.01
WQ0001906000	TX0027952	CITY OF BRYAN: Atkins Street Power Station	To Fin Feather Lake, thence to Country Club Branch and Country Club Lake, then to Burton Creek, to Carters Creek and then to Navasota River Below Lake Limestone	0.385	0.073
WQ0010426001	TX0022616	CITY OF BRYAN: Burton Creek WWTF	To an unnamed tributary, then to Burton Creek, Carter's Creek and then to the Navasota River Below Lake Limestone	8.0	12.1
WQ0013153001	TX0098663	CITY OF COLLEGE STATION: Carter Lake WWTF	To an unnamed tributary of Carters Creek, then to Carters Creek and to Navasota River Below Lake Limestone	0.0085	0.006
WQ0010024003	TX0093262	CITY OF COLLEGE STATION: Lick Creek WWTF	To Alum Creek, then to Lick Creek and to Navasota River Below Lake Limestone	2.0	1.178
WQ0010024006	TX0047163	CITY OF COLLEGE STATION: Carters Creek WWTF	To Carters Creek and then to the Navasota River Below Lake Limestone	9.5	6.33
WQ0013980001	TX0117579	CITY OF MARQUEZ: WWTF	To an unnamed tributary, then to Brushy Creek and to the Navasota River below Lake Limestone	0.04	0.03
WQ0010824001	TX0075639	CITY OF THORNTON: WWTF	To an unnamed tributary, then to Steele Creek and to the Navasota River Below Lake Limestone	0.041	0.016
WQ0004770000	TX0124401	LINDE LLC: WWTF	To an unnamed tributary, then to Brushy Creek and to Navasota River Below Lake Limestone	0.04	0.011
WQ0014879001	TX0131440	NI AMERICA TEXAS DEVELOPMENT LLC: Myers Reserve WWTF	To an unnamed tributary and then to the Navasota River Below Lake Limestone	0.075	*
WQ0001986000	TX0068021	OAK GROVE MANAGEMENT CO LLC: Oak Grove Steam Electric Station	Via Outfall 001 to an unnamed final discharge canal and into Twin Oak Reservoir, then to Duck Creek; via Outfall 002 to Twin	1610	1542

			Oak Reservoir, then to Duck Creek and to the Navasota River Below Lake Limestone		
WQ0002699000	TX0076465	OAK GROVE MINING CO LLC: Kosse Mine	N/A	*	2
WQ0012296001	TX0085456	R&B MOBILE PARK LLC DBA GLEN OAKS MOBILE HOME PARK	To an unnamed tributary, to Carters Creek and then to the Navasota River Below Lake Limestone	0.013	0.001
WQ0005138000	TX0135615	SANDERSON FARMS INC (Franklin Feed Mill)	To an unnamed tributary then to Mineral Creek, Duck Creek and to the Navasota River below Lake Limestone	0.040	0.014
WQ0003996000	TX0120146	TENASKA FRONTIER PARTNERS LTD	To an unnamed tributary, to Sulphur Creek, to Gibbons Creek Reservoir, to Gibbons Creek and then to the Navasota River Below Lake Limestone	2.5	0.764
WQ0004002000	TX0002747	TEXAS A&M UNIVERSITY	To an unnamed tributary, then to Wolf Pen Creek, to Carters Creek and then to the Navasota River Below Lake Limestone	0.93	0.58
WQ0002120000	TX0074438	TEXAS MUNICIPAL POWER AGENCY: Gibbons Creek Steam Station	N/A	*	1.14
WQ0002460000	TX0083101	TEXAS MUNICIPAL POWER AGENCY: Gibbons Creek Lignite Mine	To Lake Carlos visa Outfall 001, to Big Branch and to an unnamed tributary, to Gibbons Creek and then to Navasota River Below Lake Limestone; the discharge route for Outfall 008 is to unnamed tributaries, to Gibbons Creek and to Navasota River Below Lake Limestone	Self Report	3.888
WQ0001176000	TX0001368	US SILICA CO: Kosse Plant	Via Outfall 003 to an unnamed tributary, to White Branch, to Steele Creek and to Navasota River Below Lake Limestone; and via Outfall 001, 002, 004 and 005 to White Branch, to Steele Creek and then to the Navasota River Below Lake Limestone	2.5	1.6
WQ0010231001	TX0071790	CITY OF NAVASOTA	To Cedar Creek; thence to the Navasota River Below Lake Limestone	1.8	0.637
N/A	TXG920363	FEATHER CREST FARMS INC.	No discharge, waste application fields only in the Navasota River Below Lake Limestone watershed	Land application of 8,566 tons dry litter and 28.8 MG of liquid waste annually to 663 acres	

2.5.1.2 Stormwater General Permits

When evaluating stormwater for 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 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.

Phase 1 MS4 permits are associated with large urban areas (>100,000 population) and as such, no permits of this nature occur for the Navasota River watershed. Discharges of stormwater from a Phase II MS4 area (population >50,000 but <100,000), industrial facility, construction site, or other facility involved in certain activities are required to be covered under the following TPDES general permits:

- TXR040000 – stormwater Phase II MS4 general permit for urbanized areas
- TXR050000 – stormwater multi-sector general permit (MSGP) for industrial facilities
- TXR150000 – stormwater from construction activities disturbing more than one acre
- TXG110000 – concrete production facilities
- TXG340000 – petroleum bulk stations and terminals

Three of these permits (MS4, MSGP, and construction) pertain solely to stormwater discharges. The other two (concrete production facilities and petroleum bulk stations and terminals) also authorize the discharge of processed wastewater as discussed above under TPDES General Wastewater Permits.

Active stormwater general permits pertaining to the stormwater flow in the Navasota River watershed on December 3, 2014 includes permits for concrete production facilities (TXG11), construction activities disturbing greater than one acre and part of a larger development (TXR15), MS4 for urbanized areas (TXR04), and a multi-sector general permit for industrial stormwater discharge (TXR05). Of the 153 stormwater general permits issued to facilities in operation in the watershed, 92 of the facilities are found in Brazos County. The remaining facilities with stormwater issued permits are found in Grimes (23), Limestone (22), Leon (8), Robertson (6), and Freestone (1) counties. Brazos county stormwater general permits include those for construction, concrete production, MSGP, and MS4 Phase II sites. Only five large stormwater permits exist and account for the bulk of permitted stormwater in the watershed (Table 6~~Table 6~~).

Table 6. Phase II MS4 permits associated with the TMDL area watershed.

Regulated Entity Name	NPDES Permit Number
Brazos County	TXR040172
City of Bryan	TXR040336
City of College Station	TXR040008
Texas A&M University	TXR040237
Texas Department of Transportation	TXR040181

2.5.1.3 Sanitary Sewer Overflows

Sanitary sewer overflows (SSOs) are unauthorized discharges of wastewater 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. Information regarding SSO occurrences in the watershed is directly reported by the permitted entity to EPA and is maintained in the Enforcement and Compliance History Online database (EPA 2017). Data presented in this database may not represent all SSOs nor to permitted entities always know when an SSO occurs. As of January 1, 2016, only 54 SSOs were reported in the watershed (Table 7~~Table 7~~).

Table 7. ECHO data on reported permitted entities when an SSO occurs.

TPDES Permit No.	NPDES No.	Facility	Number of SSOs	Total Volume (gal)	Median SSO Volume (gal)	Median SSO Duration (hr)
WQ0013931001	TX0116378	CITY OF ANDERSON: WWTF	No SSOs reported			
WQ0010426001	TX0022616	CITY OF BRYAN: Burton Creek WWTF	48	8,095	50	2
WQ0013153001	TX0098663	CITY OF COLLEGE STATION: Carter Lake WWTF	No SSOs reported			
WQ0010024003	TX0093262	CITY OF COLLEGE STATION: Lick Creek WWTF	No SSOs reported			
WQ0010024006	TX0047163	CITY OF COLLEGE STATION: Carters Creek WWTF	No SSOs reported			
WQ0013980001	TX0117579	CITY OF MARQUEZ: WWTF	No SSOs reported			
WQ0010824001	TX0075639	CITY OF THORNTON: WWTF	No SSOs reported			
WQ0012296001	TX0085456	R&B MOBILE PARK LLC DBA GLEN OAKS MOBILE HOME PARK	No SSOs reported			
WQ0010231001	TX0071790	CITY OF NAVASOTA	6	150,800	5,200	2.5

2.5.2 Unregulated Sources

Unregulated sources of bacteria can originate from human and non-human activities and are usually nonpoint sources. They include wildlife, feral hogs, and agricultural animals, as well as agricultural activities, land application fields, urban runoff, failing onsite sewage facilities, and domestic pets.

2.5.2.1 Wildlife and Unmanaged Animal Contributions

While developing TMDLs, it is important to identify and include animal and wildlife bacteria contributions within the watershed as fecal indicator bacteria reside within the intestines of mammals and birds, and are released with their waste. Wildlife and unmanaged animals frequently congregate around streams and riparian areas where concentrated waste can be deposited directly into the water body or nearby land as a direct source of bacteria.

Quantitative estimates of wildlife numbers are difficult and sometimes impossible to calculate accurately. For this reason, only approximate numbers for deer and feral hogs are calculated using Texas Parks and Wildlife Department surveys conducted within the watershed, and stakeholder feedback respectively.

Feral hog estimates are based on watershed stakeholder feedback and reflect the importance of habitat. Estimates of 8ac/hog in wetlands and 13ac/hog in forests were derived yielding a watershed total of 36,827 hogs.

The deer population density is estimated at 1 deer for every 32 acres of land suitable for the deer (hay pasture, herbaceous, shrub/scrub, cropland, forests). This gives an estimate of 28,392 deer and is based on annual survey data from the Texas Parks and Wildlife Department.

Numerous other wildlife species reside in the Navasota River watershed and rely on the river, its tributaries and the habitat across the watershed for their survival. The quality and quantity of riparian habitat throughout the watershed naturally concentrates many of these wild animals near water bodies where their deposited fecal matter can have a more direct effect on instream water quality than that deposited in upland areas farther from the stream network.

2.5.2.2 Non-Permitted Agricultural Activities and Domesticated Animals

Livestock can contribute to bacteria levels within a watershed by directly depositing fecal matter in or near the waterbody and across the landscape. Use of manure as fertilizer may also contribute *E. coli* to the water body in some cases, but is largely dependent upon the time between application and the next runoff event.

The number of livestock that are found within the Navasota River watershed was estimated from county level data obtained from the 2012 Census of Agriculture (USDA NASS, 2014b). The county level data were refined to better reflect actual numbers within the watershed. To accomplish this, the total area of each county in the watershed was defined. Subsequently, land use and land cover in those portions of each county in the watershed were defined as either “Herbaceous/ Grassland” or “Hay/ Pasture” in the 2011 National Land Cover Dataset (USGS, 2014). A ratio was then developed by dividing the selected land use area of the watershed area within a county by the total area of the county. This ratio was then applied to the county level data. Table 8~~Table 8~~ shows the grazing livestock populations within the watershed.

Table 8. Grazing livestock populations in the watershed (USDA 2012).

County	Livestock*			
	Cattle	Horses	Goats	Sheep
Brazos	18,501	1,978	1,314	590
Grimes	23,705	1,274	484	78
Leon	12,104	662	414	83
Limestone	7,723	442	248	75
Madison	5,528	51	149	52
Robertson	24,477	215	515	264
TOTAL	**92,038**	**4,622**	**3,122**	**1,142**

*The number of heads from 2012 census was obtained and divided by the county area (mi^2) to get #/mi^2. The county area in watershed was calculated and multiplied by the previous #/mi^2 to get the final livestock head in the table.

2.5.2.3 Onsite Sewage Facilities

Onsite sewage facilities (OSSFs), or septic systems, are a source of bacteria if they are not designed or maintained correctly. The systems are private, residential, and usually do not contribute to bacteria levels if they are properly designed and operated. OSSFs are designed to let solids from household wastewater settle in an aerated chamber or septic tank. After settling, water in the tank flows out to a distribution system that consists of either perforated pipes or an above ground sprinkler system. If the OSSF is functioning properly, bacteria contribution to the ground and surface waters are expected to be nonexistent. However, if system failures occur, bacteria can enter the ground and surface waters. Failure rates depend predominately on soil suitability, system age, and appropriate system maintenance. Estimates for the Navasota River watershed were derived by discussing failures with County Designated Representatives is about 10.3%.

The number of OSSFs expected in the watershed was derived by applying a multifaceted estimation approach that uses 2010 US Census Bureau household estimates, 911 address data, and satellite imagery to approximate the number and location of OSSFs (Gregory et al. 2013). Using this approach, approximately 17,149 OSSFs are presumed to be in the watershed; however, this number is continually expanding. Of these, 1,747 OSSFs may be failing based on the estimated 10.3% failure rate.

2.5.2.4 Domestic Pets

Dogs and other urban animals can also contribute fecal bacteria to water bodies. The American Veterinary Medical Association (AVMA) estimates .584 dogs per household. Using 2010 US Census Bureau data, the number of households within each county in the watershed were estimated. Combining AVMA estimates with household numbers allowed a watershed estimate for dogs to be established (Table 9~~Table 9~~).

Table 9. Estimates of dog population in the watershed (AVMA 2012; U.S. Census Bureau 2010).

County	Households	Estimated Dog Population
Brazos	50,616	29,559
Grimes	3,582	2,092
Limestone	1,369	799
Leon	1,565	914
Madison	622	363
Robertson	2,764	1,614
TOTAL	**60,518**	**35,341**

2.5.2.5 Bacteria Survival and Die-Off

Bacteria are living organisms with differing rates of survival and die-off that vary by organism. Research has shown that fecal bacteria such as *E. coli* and other enteric organisms are able to survive and reproduce in sediment, soil, water, and other media for varying lengths of time depending on ambient conditions within each location. Bacteria fate research has helped to better understand this process, but much remains unknown. The implications of variations in factors influencing this die-off cannot be fully understood. Further, enteric bacteria reproduction in the environment is less studied and not well understood. However, neither reproduction nor die-off rates of indicator bacteria were considered in the bacteria source loading estimates for the watershed TMDL.

SECTION 3

DEVELOPMENT OF BACTERIA TOOLS

A successful TMDL is created, in part, by observing and linking the relationship of the pollutant sources and the water body. Once the relationship between the pollutant and the water body is linked, it is possible to determine the bacteria loadings within the water body. In the Navasota River watershed, to understand the linkage between the water body and the bacteria, two stages of development were utilized. This section describes the tools and methods used to compute the pollutant load.

3.1 Model Selection

Computer models allow for analytical abstractions of the reality of a system. For this project, three models have been chosen to aid in the assessment of the Navasota River: the TMDL model mechanistic model, the load duration curve (LDC) method, and the Soil Water Assessment Tool (SWAT) model. These three models allow understanding and prediction of physical processes based on theoretical principles already established, based on certain input variables. The TMDL allocation process for bacteria will assign *E. coli* loads to their sources to ensure total loads do not surpass contact recreational standards for bacteria. To create the TMDL model, the SWAT model was used to simulate streamflow for portions of the river and its impaired tributaries without stream gages in the watershed. The LDC method will allow for the estimation of bacteria loads based on SWAT model simulated streamflow and pollutant concentrations.

Mechanistic computer models provide analytical abstractions of a real or prototype system. Mechanistic models, or process models, are based on theoretical principles that represent governing physical processes that determine the response of certain variables, such as stream flows and bacterial concentrations, to precipitation. 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 existing and allowable load estimations by utilizing the cumulative frequency distribution of streamflow and measured pollutant concentration data (Cleland, 2003). In addition to estimating instream loads, LDCs identify hydrologic conditions under which impairments are typically occurring. This information is 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, often associated with bacteria TMDLs, which constrain the use of more powerful mechanistic models. Further, the Bacteria TMDL Task Force appointed by the TCEQ and the Texas State Soil and Water Conservation Board (TSSWCB) supports application of the LDC method within their three-tiered approach to TMDL development (TWRI, 2007). The LDC method provides a means to estimate the difference between bacteria loads and relevant criterion. Further, they can give indications of broad sources of the bacteria such as point source and nonpoint sources.

The SWAT model was developed by the USDA Agricultural Research Service and is capable of simulating stream flow and water quality parameters. The SWAT model is a watershed-scale hydraulic transport model that uses a series of inputs to simulate or model water quantity and quality changes within a system. Model inputs include topographic and meteorological data, land use, land management data, soils, hydrologic data, irrigation applications and withdrawals, groundwater recharge, basin storage, and crop growth. SWAT is a continuous time step model that generates outputs on a daily time step. In this project, the SWAT model was used solely to predict daily stream flow at ungaged locations within the watershed. These flows were then used for developing LDCs at these locations.

3.1.1 Limitations and Model Uncertainty

Primary contact recreation criteria are currently applicable to all streamflows; therefore, the allocation process must consider all streamflow conditions ranging from low flows to high flows. The TMDL allocation tool, therefore, must be capable of characterizing streamflow and bacteria loads at desired locations under a variety of environmental conditions experienced in the watershed. If a mechanistic modeling tool is applied, it must be able to simulate bacterial loading responses to streamflow during base flow, rainfall runoff, and those intermediate conditions between. The type of mechanistic tool with capabilities to simulate all these complexities is often referred to as a combined watershed loading and hydrologic/water quality model. These models simulate the hydrologic response of the watershed's land uses and land covers to rainfall, route runoff water through the conveyance channels of the watershed, add in point source contributions, and may include other hydrologic processes such as interaction of surface waters with shallow ground water.

Admittedly, streamflow processes requiring simulation are complex; however, these processes are generally better understood and more readily simulated than the bacterial processes. Regardless, mechanistic bacteria modeling has progressed significantly over the last several decades with increasing computing power. Data limitations are the primary factor limiting bacteria mechanistic modeling. Bacteria behavior varies widely from location to location. Thus the application of mechanistic bacteria models is confounded through generalized assumptions regarding bacteria fate and transport. This can greatly affect modeling uncertainty and model outputs. Therefore, more simplistic approaches that rely on known information are preferred.

Modeling limitations are exacerbated through model uncertainty that largely stems from uncertainty within the multiple input data sources. Precipitation presents the largest source of uncertainty in hydrologic modeling due to measurement errors caused by wind, rain, or snow, differences between gage-based areal mean and the true areal mean, and unsampled rainfall and temporal variability. Model structure uncertainty occurs where the model is unable to represent and accurately simulate the physical processes happening in the system, this level of uncertainty is often difficult to assess and quantify. Model parameters are another type of uncertainty, including calibrating model parameters and other model parameters. Output data uncertainty is the uncertainty where there is measurement uncertainty within the calibration process due to USGS gage errors.

Uncertainty in this project is based mostly in the limitations of the SWAT model. In this particular project, the lack of USGS streamflow gages will cause problems in calibrating and validating the simulation streamflow outputs. There are only two active streamflow gages within the river basin, both of which are located in the middle of the watershed. This means none of the tributary rivers or the southern region of the watershed will be calibrated or validated. It must be assumed the streamflow values simulated are close to their true values after calibration and validation of the watershed, although there is no way to verify streamflow outputs from the ungauged reaches.

3.1.2 Navasota Data Resources

Streamflow and *E. coli* data availability were used to provide guidance in the allocation tool selection process. As mentioned, information and data necessary to allow adequate definition of many physical and biological processes influencing in-stream bacteria concentrations for mechanistic model application are largely unavailable. Therefore, these limitations became an important consideration in the allocation tool selection process. Additionally, streamflow data are quite limited at monitoring locations in the watershed necessitating the use of a mechanistic model to predict streamflow. Data resources utilized to complete watershed SWAT modeling include Lake Limestone release data, topography, watershed boundary, the cropland data layer, gSSURGO soils data, national hydrography dataset, and daily temperature and precipitation as described in the quality assurance project plan.

To calibrate and validate the simulated output streamflow, daily and monthly streamflow data from USGS gages were used. Streamflow records are readily available from the USGS, which operates two gages on the Navasota River. The most upstream gage (08110500 aka Easterly) is in AU 1209_05 of the Navasota River below Lake Limestone and has the longest available data record. The currently active downstream gage (08110800 aka OSR) is located in AU 1209_04 and is closer to the middle of the watershed. Its data record is much shorter than the upstream gage (Table 10~~Table 10~~). Other gages have been operated on the main stem of the river in years past, but were discontinued due to natural river channel migration. However, none of the gages allow streamflow estimates for impaired AUs to be made. Therefore, streamflow estimates derived via the SWAT model are necessary for calculating *E. coli* loads.

Bacteria concentrations were measured at different TCEQ stations located on the main channel and in the tributary creeks (Table 11~~Table 11~~). Most samples were collected by the Brazos River Authority through their Clean Rivers Program monitoring efforts. TCEQ and TWRI have also performed special project monitoring in the watershed that produced usable data for this TMDL assessment.

Table 10. Basic information on the USGS streamflow gages in the project area.

Gage No.	Site Description	Assessment Unit	Daily Streamflow Record (Beginning and end date)
08110500	Navasota Rv nr Easterly, TX	1209_05	March 1924 - present
08110800	Navasota Rv at Old San Antonio Rd nr Bryan, TX	1209_04	April 1997 – present

Table 11. Summary of basic information on the TCEQ monitoring stations.

AUID	Water Body Name	Data Date Range	Station	No. Samples	2014 Texas IR Geometric Mean
1209_03	Portion of Navasota River from confluence with Sandy Branch upstream to confluence with Shepherd Branch in Madison County	Sept 2001 – Feb 2010	16398	57	91.35
1209_05	Portion of Navasota River from confluence with Camp Creek upstream to Lake Limestone Dam in Robertson County	Jan 2001 – Feb 2016	11877	91	148.59
1209E_01	Wickson Creek	Sept 2001 – Aug 2007	11789	27	313.66
1209H_01	Duck Creek	Sept 2001 – July 2012	16389	55	397.77
1209H_02	Duck Creek	Sept 2001 – Aug 2007	16390	36	317.13
1209I_01	Gibbons Creek	Sept 2011 – July 2011	11756	50	168.27
1209I_02	Gibbons Creek	Feb 2007 – May 2015	18800	32	137.16
1209J_01	Shepherd Creek	Oct 2009 – March 2011	11790	12	426.85
1209K_02	Steele Creek	Sept 2009 – Aug 2011	16384	24	218.4

Weather inputs are a significant factor affecting SWAT model simulations. Increasing the number of weather station inputs decreases uncertainty as values interpolated between stations are improved. Stations used in SWAT were chosen based on location and data availability. Criteria considered included:

- located within the counties adjacent to the watershed
- contained > 70% of the daily data values from the data range of 1979 to 2016

These criteria ensured that weather stations chosen were within the watershed or close to it. In total, 16 precipitation stations were chosen and 7 temperature stations were chosen based on these criteria (Table 12Table 12). Precipitation data is in millimeters and temperature is in degrees Celsius.

Table 12. Precipitation and temperature stations from the National Oceanic and Atmospheric Administration.

Station ID	Station Name	Data Type	Data Date Range
GHCND:USC00410297	AQUILLA 1 SSE TX US	P	1992 - 2016
GHCND:USC00411026	BRANDON TX US	P	1992 - 2013
GHCND:USC00411045	BREMOND TX US	P	1979 - 2016
GHCND:USC00411188	BUFFALO TX US	P	1979 - 1988
GHCND:USC00411596	CENTERVILLE TX US	P & T	1979 - 2016
GHCND:USC00414182	HILLSBORO TX US	P & T	1979 - 2016
GHCND:USC00414505	ITASCA TX US	P	1992 - 2016
GHCND:USC00415477	MADISONVILLE TX US	P & T	1979 - 2016
GHCND:USC00415869	MEXIA TX US	P & T	1979 - 2016
GHCND:USC00415904	MIDWAY 4 NE TX US	P	1979 - 2015
GHCND:USC00416496	OAKWOOD TX US	P	1980 - 2010
GHCND:USC00417586	RICHARDS TX US	P	1979 - 2013
GHCND:USC00419004	THORNTON 1 SSE TX US	P	1979 - 2016
GHCND:USC00419491	WASHINGTON STATE PARK TX US	P & T	1979 - 2016
GHCND:USC00419715	WHITNEY DAM TX US	P & T	1979 - 2016
GHCND:USW00003904	COLLEGE STATION EASTERWOOD FIELD TX US	P & T	1979 - 2016

P = precipitation; T = temperature

3.1.3 Soil Water Assessment Tool (SWAT) Model

The SWAT model is a continuous daily time step, physical hydrologic model that operates within the ArcGIS platform. The model simulates watershed and landscape drive properties including hydrology, erosion, soil, crop growth from the input climate data. Additionally, nutrient, pesticide, and fecal bacteria fate and transport can also be modeled.

For the purposes of this TMDL, a SWAT model was constructed for the Navasota River below Lake Limestone watershed. Lake Limestone discharge was incorporated into the model as an inlet and the outlet is located at the river's confluence with the Brazos River. In short, a digital elevation model (DEM) is used to define the extent of the watershed and drive water routing throughout the watershed. This is paired with the National Hydrography Dataset (NHDplus) to determine the river channel location, the direction of flow, and to inform flow accumulation in the channel. Through this process, the tributary network is defined and subbasins are also created.

Stream flow simulation calibration, validation, sensitivity analysis, and uncertainty was performed with SWAT-Calibration and Uncertainty Programs (SWAT-CUP) using the Sequential Uncertainty Fitting 2 (SUFI-2) program. The Navasota River SWAT model was calibrated at the south most USGS station. Calibrations were performed on a monthly scale but run on a daily time step once calibration and validation were complete. The SWAT model was run for 500 iterations using a varying number of parameters and ranges for the watershed. The model was accepted and deemed satisfactory with a Nash-Sutcliff coefficient of > 0.50 in accordance with the project QAPP.

3.2 Methodology for SWAT Model Streamflow Output

The methodology for developing the SWAT model utilizes data resources mentioned to model the hydrologic cycle of the watershed by calculating the watershed's water balance. Inputs (precipitation) are quantified, and outputs (runoff, evapotranspiration, and infiltration) are subtracted to model the total soil water content. The model uses previously developed empirical formulas to link different physical processes together to achieve the water balance of the watershed. The development of the SWAT model for the Navasota watershed is cataloged in the sequential steps listed below.

3.2.1 Watershed Delineation

Watershed delineation is performed using a DEM raster grid and processed using the Automatic Watershed Delineation feature of ArcSWAT. This is the step where flow direction and flow accumulation within the watershed are established. The threshold area value used is 800 hectares (ha) to ensure the created streams contain the necessary stream network. The higher the value, the fewer cells and less data produced from the DEM.

To simulate a controlled discharge from Lake Limestone, an inlet was added at the dam site. This allows daily discharge data from the dam, gathered from the Brazos River Authority Watershed, to be entered. This location defines the upper extent of the modeled watershed.

To define basin and subbasin areas, watershed outlet points are inserted at the TCEQ surface water quality monitoring stations, USGS gage locations, and at the end of the Navasota River segment. The outlets at the TCEQ and USGS stations ensured the daily streamflow values would be generated at each point to allow for TMDL development use.

3.2.2. Land Use

Land use is of utmost importance in the establishment of a SWAT model. Land use is one of the main factors that determine how the watershed reacts to precipitation. When precipitation occurs, the water will evaporate, become intercepted by trees, plants or buildings, infiltrate into the ground, or runoff into stream channels. The SWAT model uses the SCS curve number method to predict runoff expected from within the watershed.

The SCS Runoff Curve Number Method, shown below in Equation 1 and 2, was developed by the US Department of Agriculture (USDA) to estimate storm runoff.

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

$$Q = \frac{(P - 0.2 \cdot S)^2}{(P - 0.8 \cdot S)} \qquad \text{(Eq. 2)}$$

Where:

Q = runoff (in)

P = rainfall (in)

S = potential maximum retention after runoff begins (in)

I_a = initial abstraction

This method considers initial abstraction (I_a) as the water lost before runoff begins; this includes the water that is lost to infiltration as well as surface storage and interception. Typically I_a is determined by overlying vegetation and soil properties. Empirical analysis of typical watersheds has approximated I_a to be equal to $I_a = 0.2 \times S$. This produces the simplified SCS runoff curve equation presented in Equation 1. The S variable (calculated using Equation 3) is described by a Curve number (CN) that ranges from 0 – 100 and was based on the hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition.

$$S = \frac{1000}{CN} - 10 \qquad \text{(Eq. 3)}$$

Land use is quantified within each subbasin and is computed as hydrologic response units (HRUs). The number of HRUs for the basin was limited to 2500. Each HRU consists of land parcels with similar land use, soil, slope, and management. Each HRU acts as a single response unit. The land use for the model is the Cropland Data Layer and gSSURGO soils. The cropland data layer and gSSURGO soils were used to retain a realistic representation of the watershed.

3.2.3. Weather Inputs

Weather inputs are critical for accurately estimating watershed inputs and in simulating evaporation and transpiration or, evapotranspiration (ET). ET is the value simulated as an output, or a negative, from the watershed. Within the SWAT model, potential ET (PET) uses the Priestley-Taylor method as default PET method. It was not changed within the model. Variables needed to calculate the ET amount are average temperature, elevation, latitude, and the months being examined. From these given input values, latent heat of vaporization, vapor pressure, and net solar radiation are computed. This allows the amount of total ET across the watershed to be simulated.

While SWAT has weather generators built into it, actual weather data is preferred if a sufficient number of stations are within or near the watershed. For this watershed, stations within counties that are in or adjacent to the watershed were utilized. In total, precipitation data from 16 stations and temperature from 7 stations were used. Data from all stations began on January 1, 1979 and ended April 25, 2016. There were 13630 values for each station. If there were no data for a given date, -99 was used in replacement to indicate a null value.

3.2.4. Calibration, Validation, Sensitivity, and Uncertainty Analysis

Model calibration, validation, uncertainty analysis, and sensitivity are important to consider when simulating events in a hydrologic model. A single site strategy using USGS gage 08110800 (Navasota River at San Antonio Road near Bryan) was used to calibrate stream flow for this model. Since the USGS data for that station were available from April 1997 to present, the data were split into a calibration and a validation period. Data from USGS gage 08110500 (Navasota River near Easterly) were also used for model validation. A model warm up period of two years was used for validation.

3.2.4.1. Calibration and Sensitivity Analysis

Sequential Uncertainty Fitting 2 (SUFI-2) is a program within SWAT-CUP that allows users to calibrate and validate outputs from the SWAT model. SUFI-2 utilizes a deterministic “trial and error” approach to calibrate a model. The process of calibration with SUFI-2 involves running multiple iterations through different, multiple, adjusted parameters until a reasonable outcome is achieved. Latin Hypercube sampling is used to identify sensitive parameters to the model. Parameters within SUFI-2 are expressed as ranges and SUFI-2 begins by assuming large parameter uncertainty within the 95% prediction uncertainty (95PPU) and calculates the 2.5% and the 97.5% levels of the cumulative distribution of the parameter output. The objective is to have all the observed values contained within 95PPU. An increase of observed values within the 95PPU usually indicates a better-simulated model. The P-factor and R-factor quantify the best fit. The P-factor is the percentage of observed values within the 95PPU. A suggested value for the P-factor is >70% for discharge. R-factor is the thickness of the 95PPU, and suggested acceptability is around 1. The Nash Sutcliffe coefficient (NSE) (Eq. 4) was used to evaluate the model compared to observed values. Using the Nash Sutcliff coefficient, according to Moriasi et al. (2007), a satisfactory model simulation for streamflow is an NSE value of ≥ .50. This was the baseline for the objective function used within SWATCUP.

$$\text{NSE} = \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n}(Y_i^{obs} - Y^{mean})^2}\right] \qquad \text{(Eq. 4)}$$

Of the twelve reaches within the SWAT model, only one subbasin was calibrated. Reach five within subbasin five was calibrated for USGS gage 08110800 Navasota River at San Antonio Road near Bryan. Since the USGS data was from April 1997 to present, the data were split into calibration and validation periods (Table 13~~Table 13~~).

Table 13. Calibration and validation dates with warm up periods for the Navasota SWAT model.

	Warm Up Period	Run Time	Total Years
Calibration	January 1998-December 1999	January 2000 – December 2008	10
Validation	January 2009 - December 2010	January 2011 – April 2016	8

SWAT-CUP ran 500 iterations between 1/1/1998 to 12/31/2008, with a two-year warm up period. A warm up period is recommended to allow the model simulations to stabilize the parameters and variables. Warm up periods can range in dates depending on the variables being examined. Since this project is only examining one variable, streamflow, the warm up period only needs to be around 2-3 years (Daggupati et al., 2015).

Ten parameters were chosen to optimize the model within SWAT-CUP (Table 14). The parameters were calibrated based on their type using a global modification term by taking initial value estimates and either multiplying them, replacing them, or adding on to them. Current values calculated within the model related to HRUs, such as soil and land use, were multiplied. This makes sense for soil and land use parameters since they vary across the watershed. This approach allows the current values to change consistently with each other. Current values related to groundwater and ESCO were replaced with a new value. This type of change is best for values that are not physical values. Values that were multiplied are shown in ranges and not exact values like the groundwater and ESCO values (Table 14).

The Navasota River watershed can be classified as a highly managed watershed due to the presence of Lake Limestone and its controlled discharge. The SWAT model initially attempts to model the watershed naturally based on precipitation events; however, due to the controlled releases from Lake Limestone, actual stream flow in the river does not respond to rainfall in a natural fashion. Thus, parameters within the watershed, when altered, may not realistically reflect hydrologic conditions in the river.

Table 14. The parameters optimized in SWAT-CUP.

Parameter	Description	Default	Range Min	Range Max	Calibrated Value
CN2.mgt	Curve number for crop areas – non-crop	25 - 92	35	98	.00796
GW_DELAY.gw	Groundwater delay (days)	31	0	500	3.47315
Alpha_BF.gw	Baseflow alpha factor (days)	.048	0	1	.08075
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	1000	0	5000	.29911
GW_REVAP.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	.02	0	500	.09911
SOL_AWC.sol	Available soil water capacity	0 - .17	0	1	0 - .17
SOL_K.sol	Saturated hydraulic conductivity	0 - 280.8	0	2000	0 - .1458
SOL_Bd.sol	Moist bulk density	0 - 1.65	.9	2.5	0 - 1.65
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	0	.01	500	0
ESCO.hru	Soil evaporation compensation factor	.95	0	1	.108366

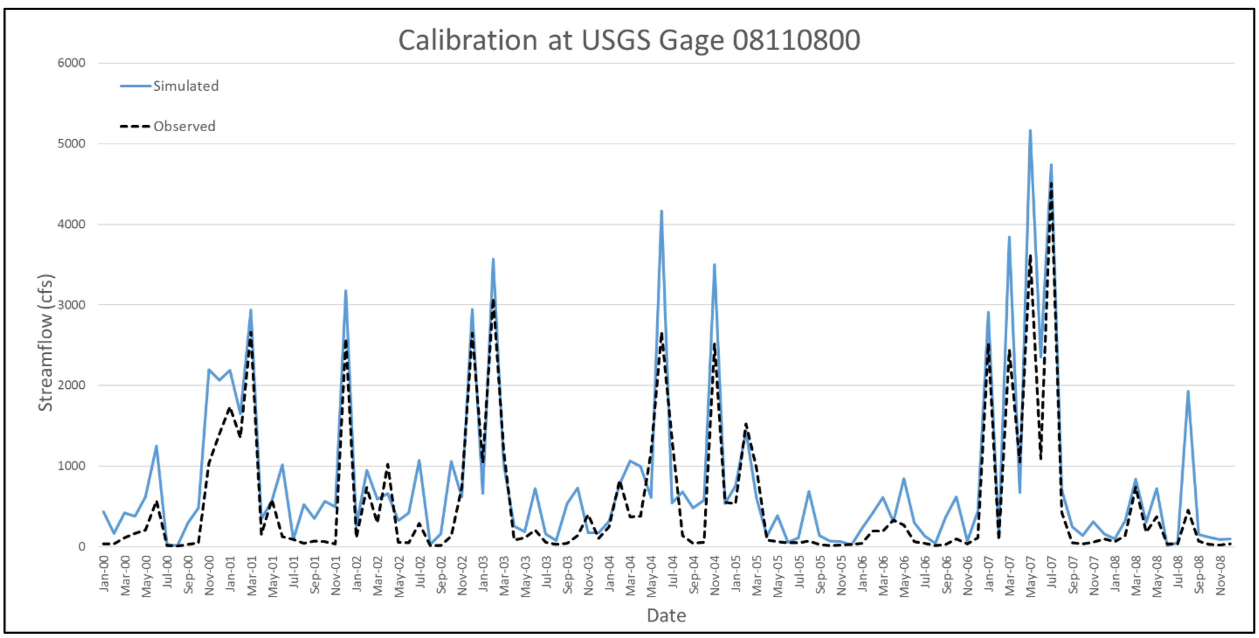

Figure 8. Observed streamflow values plotted against SWAT simulated ones.

The final NSE value for the calibrated subbasin was 0.69 and was above the minimal acceptance level of 0.5 (Figure 8Figure 8). Sensitivity analysis was evaluated by the t-Stat and the P-value. The aim of sensitivity analysis is to understand and estimate the rate of change in the output model with respect to input parameters. Sensitive parameters, when altered, will affect model output more than non-sensitive parameters. Sensitivity analysis can be local, one-at-a-time, or global. Global sensitivity analysis utilizes Latin Hypercube sampling to identify sensitive parameters. Using this method of sensitivity analysis, it is possible to determine sensitivity over the whole parameters space and identify parameter correlation.

SWAT-CUP best parameters were repeatedly put back into the model to achieve an objective function NSE of .50 or higher. Sensitivity of each parameter can be measured by looking at the t-stat values and the p-values (Table 15Table 15). Sensitive parameters will have a higher absolute t-stat value while significantly sensitive parameters will have p-values closer to 0. None of the parameters were particularly significantly sensitive.

Table 15. Parameter global sensitivity metrics.

Parameter Name	Description	t-Stat	P-Value
10:V__CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	0.13	0.89
4:V__GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0.49	0.62
5:V__GW_REVAP.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	-0.62	0.53
2:V__ALPHA_BF.gw	Baseflow alpha factor (days)	-1.37	0.17
3:V__GW_DELAY.gw	Groundwater delay (days)	3.34	0.00
11:V__ESCO.hru	Soil evaporation compensation factor	-16.18	0.00
6:R__SOL_AWC(..).sol	Available soil water capacity	21.61	0.00
8:R__SOL_BD(..).sol	Moist bulk density	-26.52	0.00
1:R__CN2.mgt	Curve number for crop areas – non-crop	-68.03	0.00
7:R__SOL_K(..).sol	Saturated hydraulic conductivity	-136.49	0.00

3.2.4.2. Validation

Validation of a model is necessary to check model validity without changing any parameters. Validation usually takes place after the model has been calibrated to sufficient standards and is done using a different data subset from the calibrated data.

The Navasota River SWAT model was validated between January 2011 and April 2016. A warm up period of two years was used (January 2009 to December 2010). The NSE coefficients comparing observed and simulated outputs for the validated model at the USGS Easterly and OSR gages were 0.79 and 0.51 respectively (Figure 9Figure 9 and Figure 10Figure 10). These values were both above the approval threshold of 0.5, thus the model was deemed acceptable.

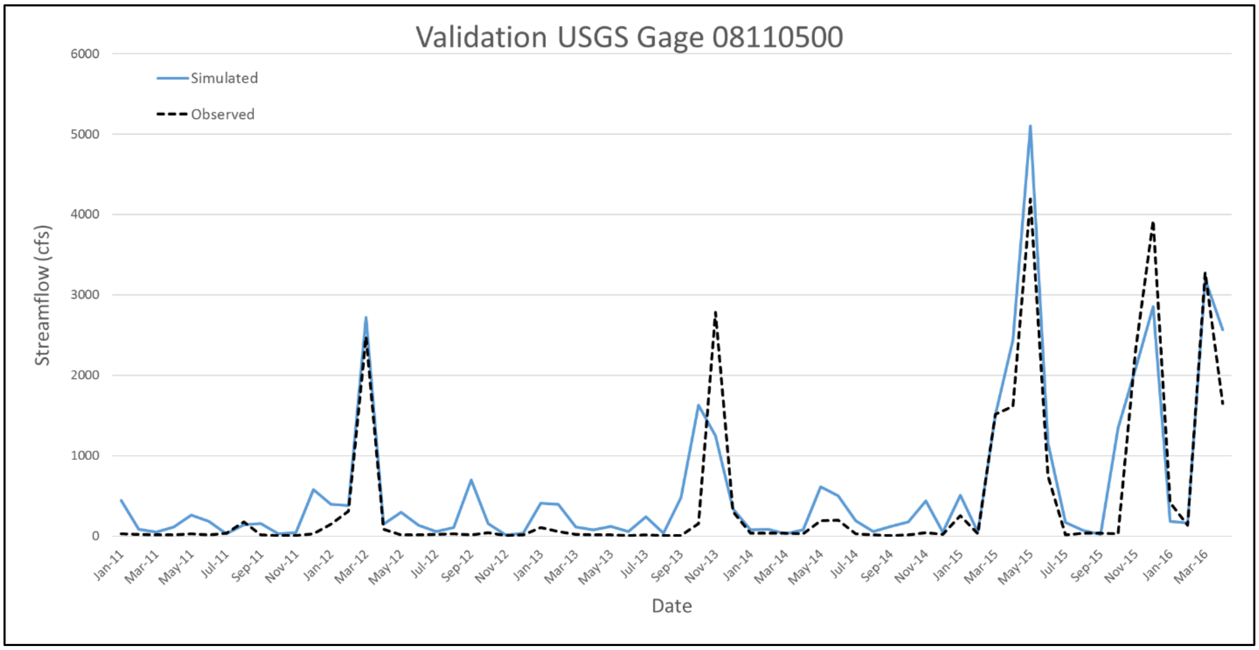

Figure 9. Model validation for USGS gage 08110500 on the Navasota near Easterly, TX.

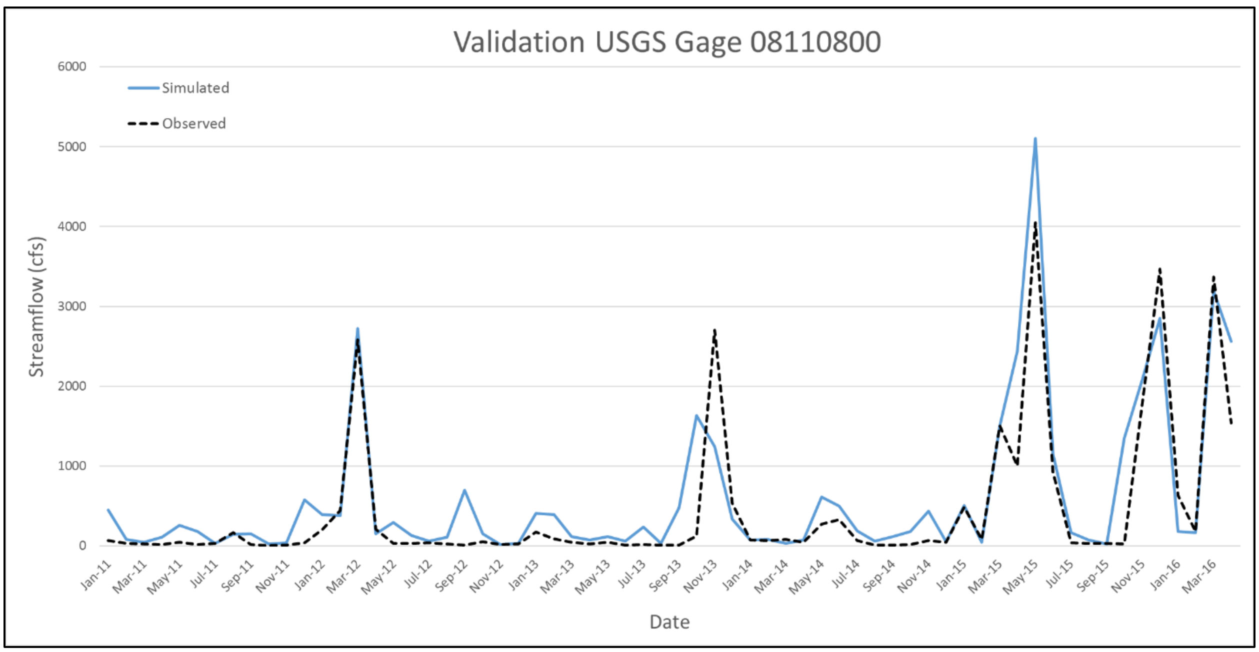

Figure 10. Model validation for USGS gage 08110800 on the Navasota River at Old San Antonio Road near Bryan, TX.

3.2.4.3. Uncertainty

Uncertainty within hydrologic models can be large and is generally divided into three categories: conceptual model uncertainty, input uncertainty, and parameter uncertainty. Conceptual model uncertainty, or structural model uncertainty, can occur when the model: 1) oversimplifies the watershed; 2) does not include some watershed processes; 3) includes unknown or unacceptable processes from the watershed; or 4) includes uncertainties that are unknown to the model and modeler. Input model uncertainties are due to input errors from all the input values. These can come from land use/land cover layers and management strategies; however, largest source of uncertainty is usually from precipitation values due to collection measurement uncertainty from wind and ungaged areas. Parameter uncertainty can occur when non-uniqueness of a parameter in inverse modeling occurs. This non-uniqueness occurs because many parameter sets can produce the same output even if the parameters values are different themselves (Abbaspour, 2015).

Figure 11~~Figure 11~~ shows the calibrated model output and its uncertainties compared to the observed values. The green bars on the 95PPU indicate the uncertainty zone between simulated model output and observed values. Ideally, observed values are captured within the 95PPU band while decreasing the 95PPU zone. The R-factor is the average thickness of the 95PPU band divided by the standard deviation of observed data and the P-factor is the percent of observed data within the 95PPU band. Ideally, the best values for the variables are as close to 1 as possible. The R-factor is .22 and the P-factor is .13 for this simulation.

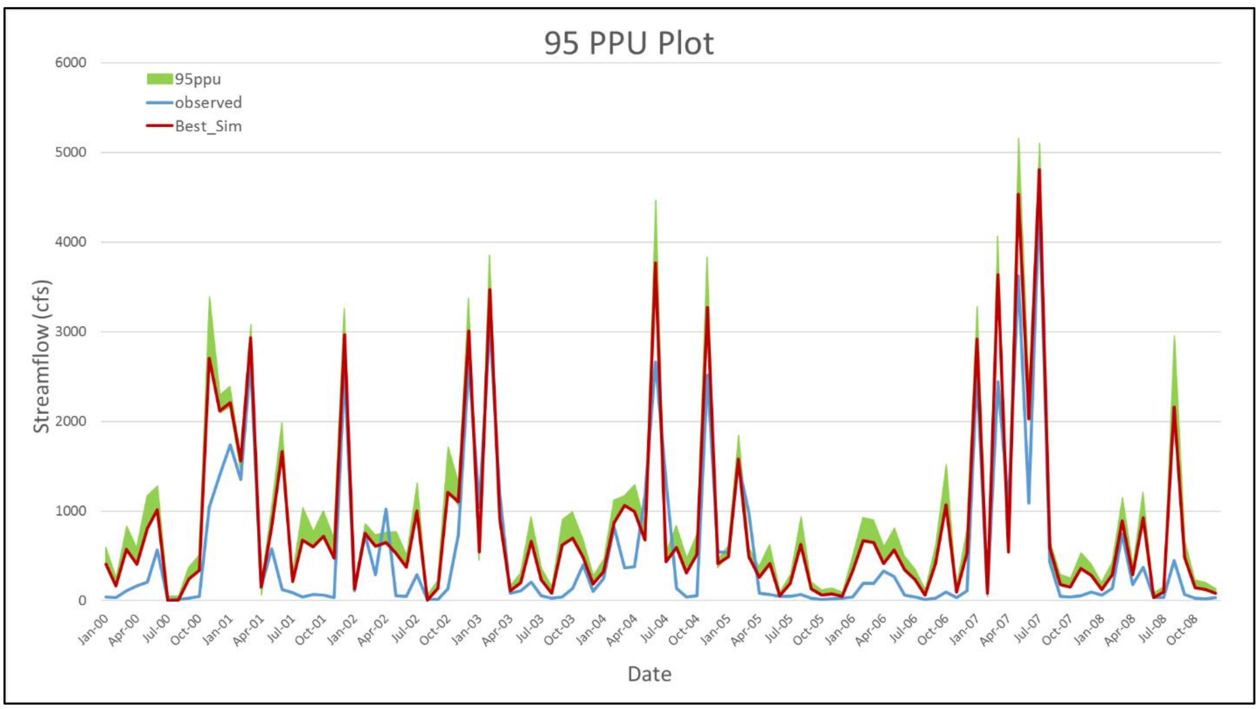

Figure 11. 95PPU plot. The green bars within the graph shows the uncertainty zones within the simulation.

3.3 Methodology for Flow Duration & Load Duration Curve Development

Load duration curves use streamflow multiplied by the water quality parameter and appropriate conversion factors to obtain maximum allowable loads over all flow conditions. LDCs are presented on a curved line and a TMDL can be expressed as a continuous function of flow through the line. A TMDL can be derived from a discrete value from a specific flow condition.

As mentioned previously, streamflow outputs from SWAT were not calibrated or validated for the tributaries or below the second USGS streamflow gage due to the lack of available data. Simulated streamflow is assumed to represent the true value at these ungaged points. Utilizing the simulated streamflow from the SWAT model and the previously discussed data resources, LDCs were established using these following steps noted below.

Step 1: Determine desired stream locations for which flow duration curves (FDCs) and load duration curves (LDCs) will be developed
Step 2: Determine the hydrologic period of record to be used in developing FDCs
Step 3: Develop daily streamflow records at desired stream locations using the SWAT model
Step 4: Develop FDCs at selected stream locations and segment into discrete flow regimes
Step 5: Develop the allowable bacteria LDCs based on relevant water quality criteria and FDC data
Step 6: Superimpose historical bacteria data on the allowable bacteria LDCs

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

3.3.1 Step 1: Determine Desired Stream Locations

Bacteria data for the impaired reaches of watershed streams are available from several SWQM stations within the Navasota River watershed. Water quality monitoring stations used in current biennial waterbody assessments were chosen for use in this assessment. These stations generally have a sufficient historic data record to develop an LDC. Data were extracted from TCEQ's Surface Water Quality Monitoring Information System (SWQMIS) https://www80.tceq.texas.gov/SwqmisWeb/.

3.3.2 Step 2: Determine Hydrologic Period and Develop Daily Streamflow Records

The period of record for creating a Flow Duration Curve should contain as much data as possible in order to capture high and low streamflow events and natural variability within the system. The majority of monitoring stations in the watershed had insufficient data to develop an adequate FDC. Therefore, the SWAT model was developed to provide a majority of the streamflow points. Consequently, the hydrologic period of record was predicted to coincide with the bacteria data availability timeframe.

For the main channel, daily hydrologic records were found from the USGS gage stations within the Navasota River watershed. Gage 08110800 Navasota River at San Antonio Road has a 20-period daily streamflow record. Station 08110500 Navasota River near Easterly has a daily record of 93 years from 1924 to present. Since the time period of collected bacteria was between January 2000 to April 2016, each station has a slightly different amount of bacteria data points, so the hydrologic period was also set to correspond with that time period.

The calibrated and validated SWAT model was run on a daily time step to gather the streamflow for that time period to develop the 16+ year streamflow record for the tributary creeks.

3.3.3 Step 3-5: FDC and LDC Methods

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

- order the daily streamflow data for the location from highest to lowest and assign a rank to each data point (1 for the highest flow, 2 for the second highest flow, and so on); compute the percent of days each flow was exceeded by dividing each rank by the total number of data points plus 1; and
- 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 MPN/100 mL) and by a conversion factor (2.44658x107), which gives a loading in units of cfu/day; and
- plot the exceedance percentages, which are identical to the value for the streamflow data points, against geometric mean criterion of *E. coli*.

The resulting curve represents the maximum allowable daily loadings for the geometric mean criterion. The next step was to plot the sampled *E. coli* data, when such data existed at the LDC locations, on the developed LDC using the following two steps:

- using the unique data for each monitoring station, 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 (2.44658x107); 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* concentration multiplied by daily streamflow) display the frequency and magnitude that 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.

3.4 FDCs for Sampling Stations within TMDL Watersheds

FDCs were developed for monitoring stations within the Navasota River watershed that were deemed impaired (Figure 12~~Figure 12~~). FDCs were developed using the period of record described in earlier sections. Exceedance values along the x-axis represent the percent of days that flow was at or above the associated flow value on the y-axis. Exceedance values near 100% occur during low flow or drought conditions while values approaching 0% occur during periods of high flow or flood conditions. This graphical procedure provides information on basic hydrological characteristics in the stream based upon flows observed within specific reaches.

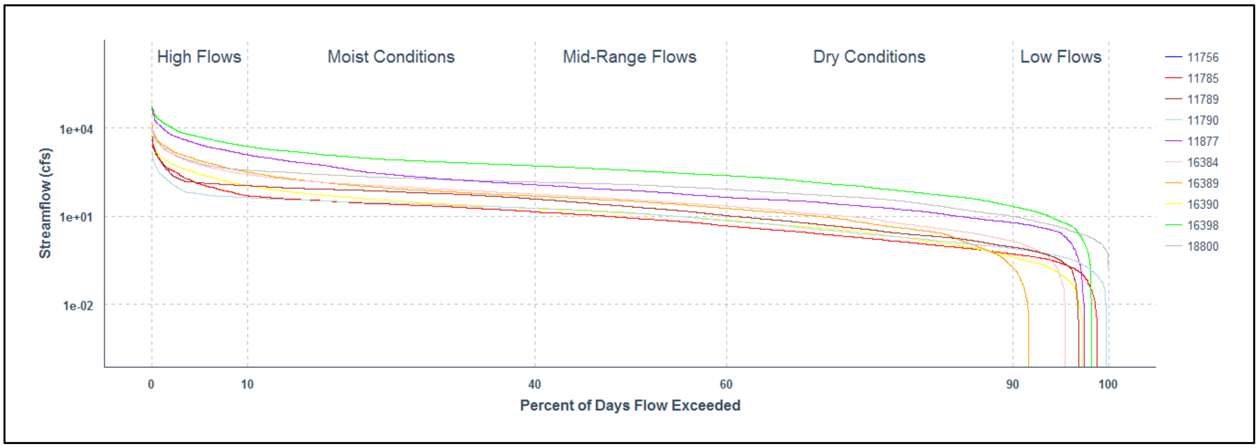

Figure 12. Flow duration curves for all ten stations within the Navasota watershed.

3.5. LDCs for Sampling Stations

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% (high flows); (2) 10-40% (moist conditions); (3) 40-60% (mid-range flows); (4) 60-90% (dry conditions); and (5) 90-100% (low flows).

LDCs for each impaired segment demonstrate the allowable load compared to the geometric mean of available data within each flow category. Flow conditions where loading exceedances occur provide information regarding when exceedances occur relative to hydrologic conditions (Figure 13~~Figure 13~~, Figure 14~~Figure 14~~, Figure 15~~Figure 15~~, Figure 16~~Figure 16~~, Figure 17~~Figure 17~~, Figure 18~~Figure 18~~, Figure 19~~Figure 19~~, Figure 20~~Figure 20~~, Figure 21~~Figure 21~~).

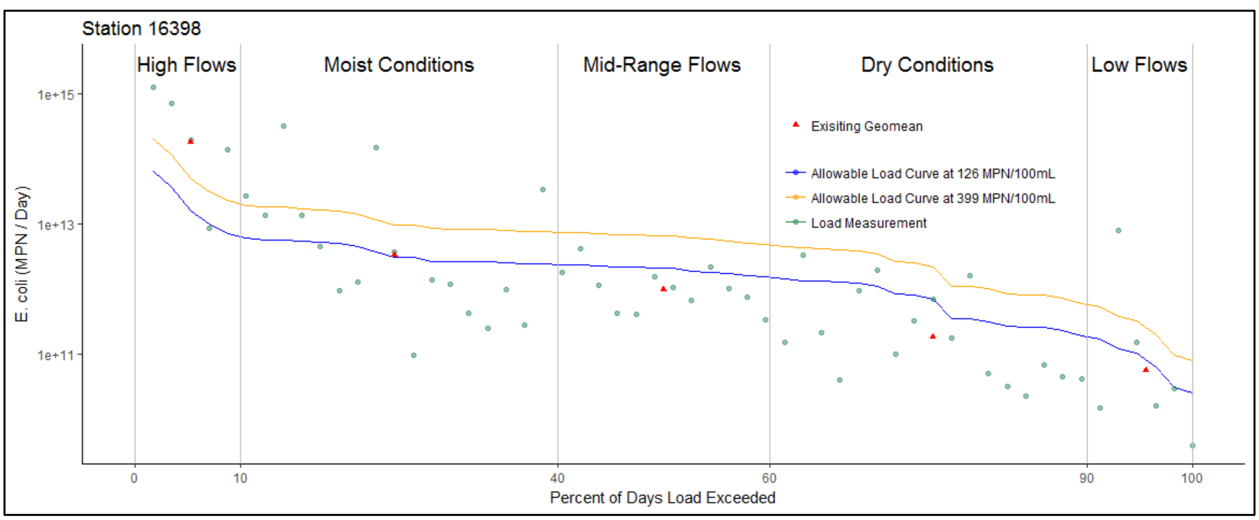

Figure 13. Load duration curve at Station 16398 Navasota River at Grimes (Segment 1209_03) for the period of September 2001 through February 2016.

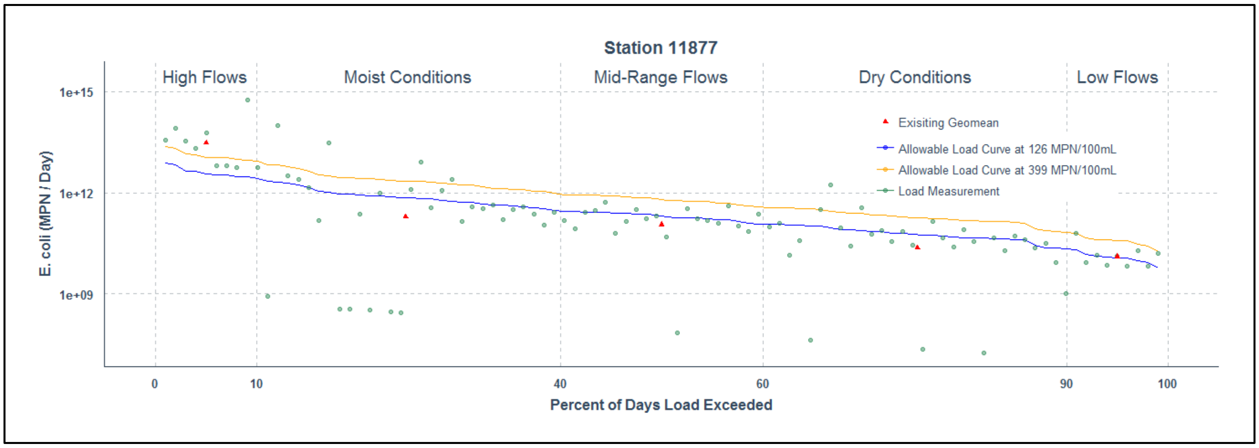

Figure 14. Load duration curve at Station 11877 Navasota River at US 79 (Segment 1209_05) for the period of January 2000 through February 2016.

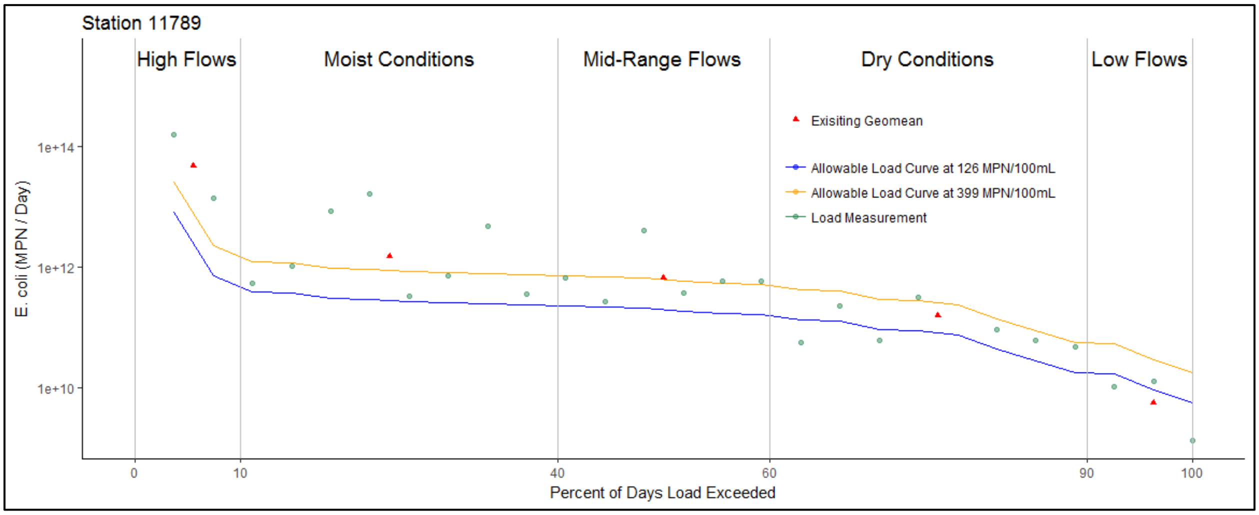

Figure 15. Load duration curve at Station 11789 Wickson Creek (Segment 1209E) for the period of September 2001 through August 2007.

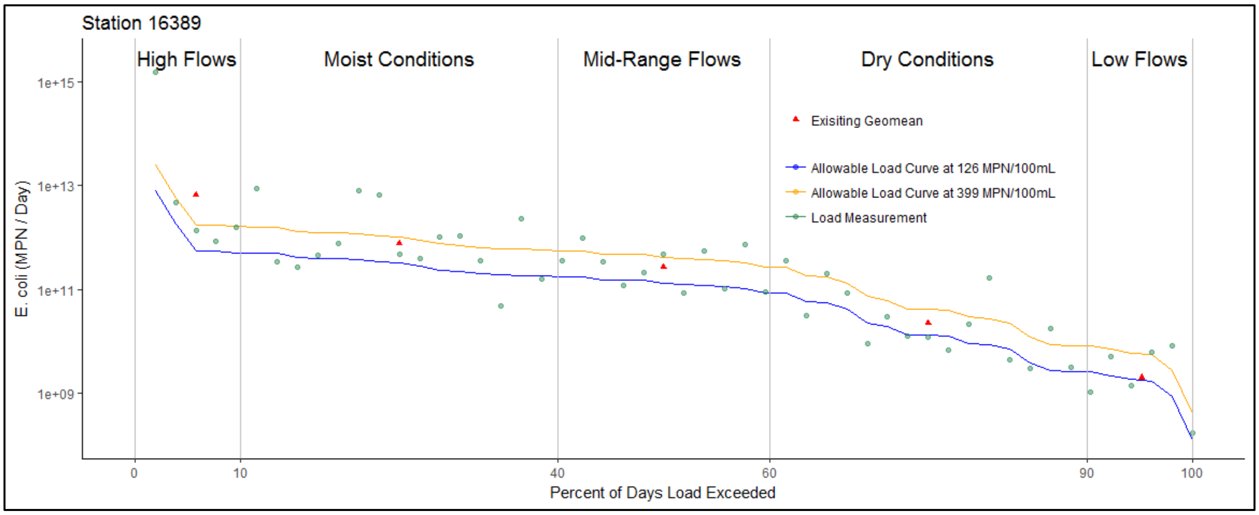

Figure 16. Load duration curve at Station 16389 Duck Creek at SH 79 (Segment 1209H__01) for the period of September 2001 through August 2015.

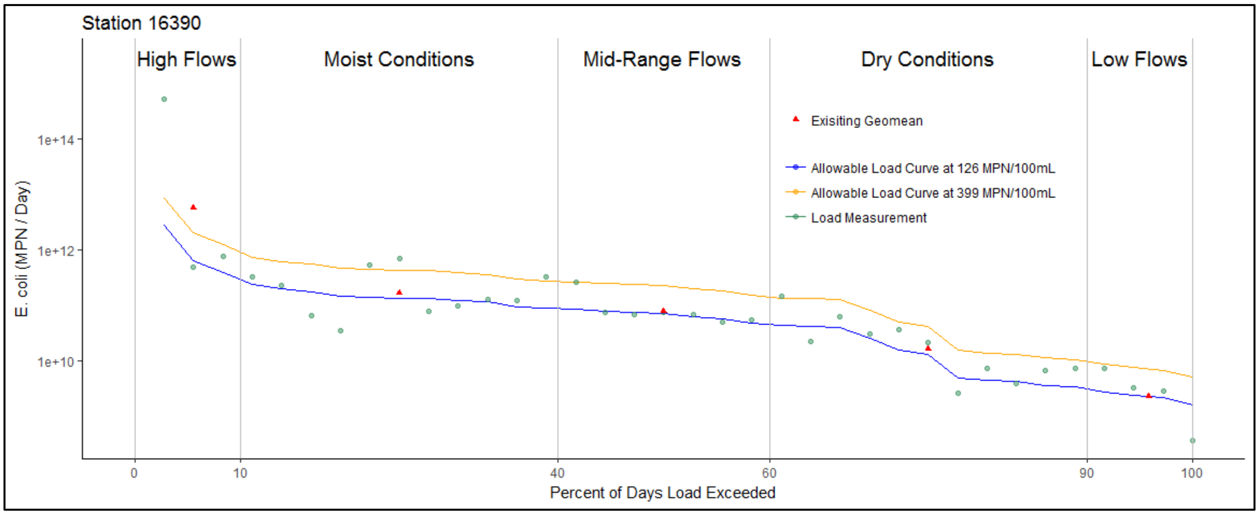

Figure 17. Load duration curve at Station 16390 Duck Creek at FM 979 (Segment 1209H_02) for the period of September 2001 through August 2015.

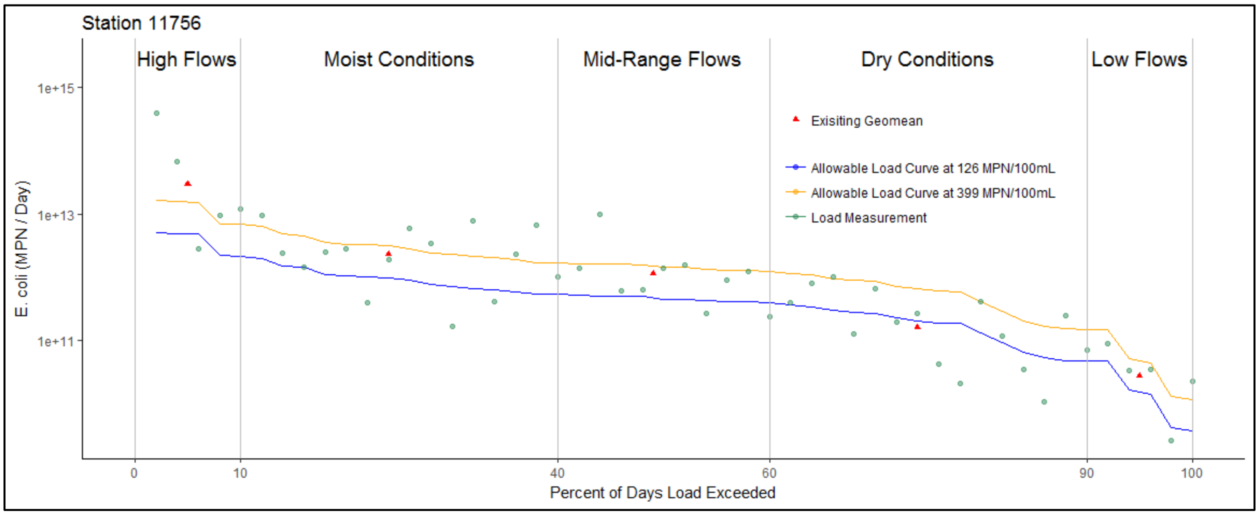

Figure 18. Load duration curve at Station 11756 Gibbons Creek at Grimes CR 190 (Segment 1209I_01) for the period of September 2001 through July 2011.

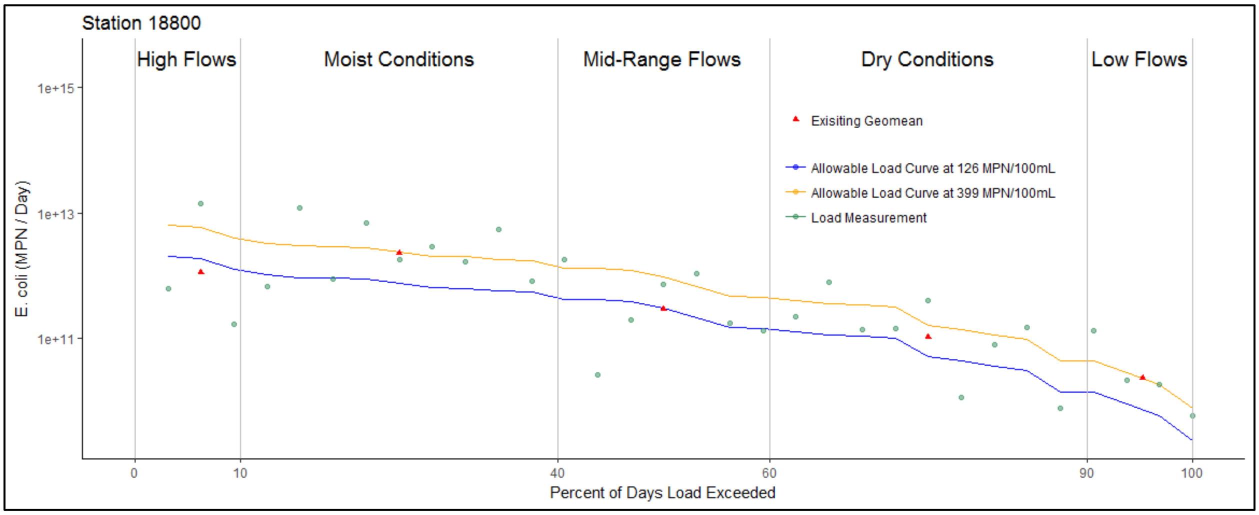

Figure 19. Load duration curve at Station 18800 at Gibbons Creek at FM 244 (Segment 1209_02) for the period of February 2007 through May 2015.

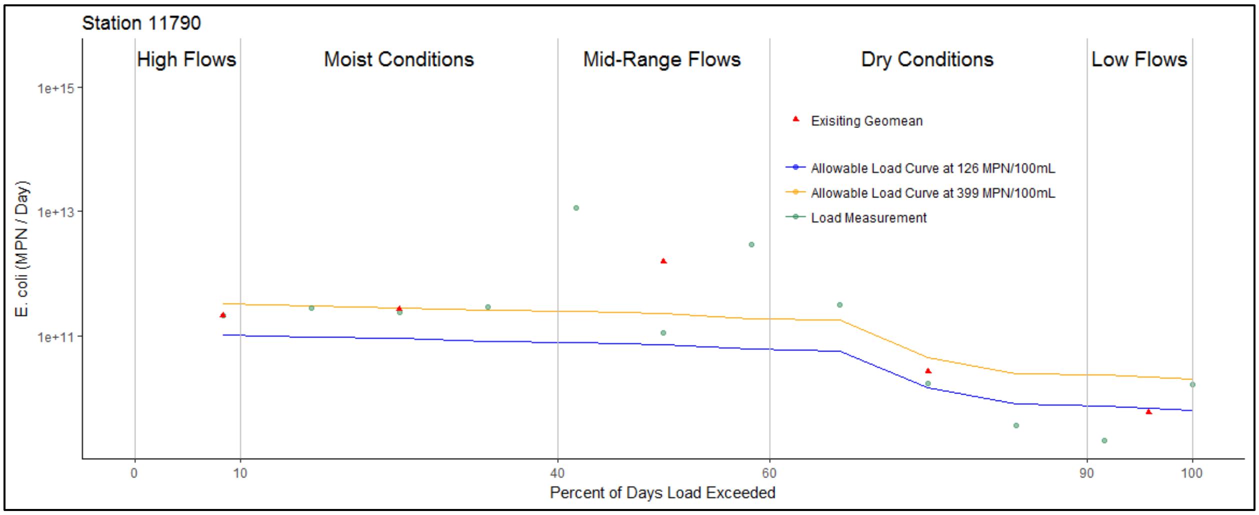

Figure 20. Load duration curve at Station 11790 Shepherd Creek (Segment 1209J) for the period of October 2009 through March 2011.

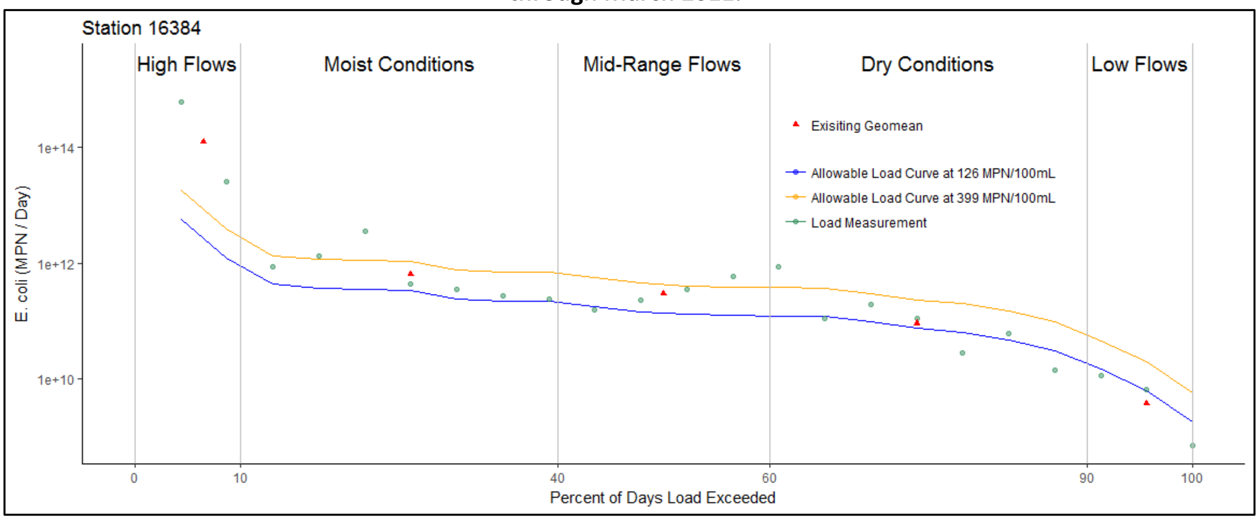

Figure 21. Load duration curve at Station 16384 Steele Creek (Segment 1209K) for the period of September 2009 through August 2011.

SECTION 4

TMDL ALLOCATION ANALYSIS

Developing the LDCs for each segment was completed in Section 3 of the report where historical bacteria and streamflow numbers were collected and assessed on a frequency distribution. The LDC method provided the information to determine the necessary reductions in bacteria loadings.

This section of the report discusses the development of the TMDL allocation for bacteria in the watershed. Endpoint identification, margin of safety, load reduction analysis, TMDL allocations, and other TMDL components are also described in the following section.

In this watershed, the TCEQ developed TMDLs on Burton Creek, Carters Creek, and Country Club Branch (Segments 1209L, 1209C, 1209D) in 2008 and implemented the plans in 2012.

4.1. Endpoint Identification

The endpoint is a measurable, quantifiable goal that all TMDLs must have. This goal indicates whether the TMDL has met its water quality target. In addition, the endpoint set for the TMDL can also serve as a criterion to evaluate future conditions. The Navasota has a TMDL endpoint set at 126 MPN/100 mL to maintain *E. coli* concentrations.

4.2 Seasonality

Seasonality, or seasonal variations, occur when streamflow and water quality experiences regular, recurring, and predictable changes. Federal regulations (40 CFR §130.7(c)(1)) state TMDLs must account for the seasonality within a watershed. Samples from warmer months (May – September) should be assessed against cooler months (November – March). The transitional months are April and October and are excluded from the analysis. The Wilcox Rank Sum test was used to evaluate the presence of different *E. coli* concentrations at each site between seasons. Only the mainstem segments of the Navasota River exhibited seasonal differences in *E. coli* concentration (Table 16~~Table 16~~) at the α = .05 level.

Table 16. Seasonality analysis of the *E. coli* data collected.

AU ID	α	P-Value	Significant Difference between Warm and Cool Months
1209_03	.05	0.001051	Y
1209_05	.05	0.008083	Y
1209E	.05	0.1161	N
1209H_01	.05	0.199	N
1209H_02	.05	0.5583	N
1209I_01	.05	1	N
1209I_02	.05	0.1358	N
1209J	.05	0.6667	N
1209K	.05	0.683	N

4.3 Linkage Analysis

Load duration curves were used to analyze the relationship between water quality and the indicator bacteria source. This relationship is essential for establishing and developing a TMDL as it suggests the types of pollution causing the impairment and allows management options to be evaluated that will aid in attaining the desired endpoint.

Generally, direct fecal deposition can be identified when there are high bacteria concentrations in low to medium streamflow levels. As flow increases, point source bacteria levels are expected to decrease and become diluted. During non-runoff-influenced flows, direct inputs to the system will increase pollutant concentrations if the magnitude and concentration of sources is substantial.

During runoff events, bacteria load contributions from permitted and non-permitted stormwater sources are highest, as runoff from rainfall is able to carry indicator bacteria from the land to the stream. This loading pattern is identified by low bacteria concentrations before a rain event followed by a rapid increase as the first flush of stormwater runoff enters the water body.

The use of load duration curves assumes a 1 to 1 ratio between the instream loading and the loadings originating from regulated and unregulated point sources. This ratio also is assumed when developing the TMDL pollutant load allocation. Pollutant load allocations are based on the distribution of loadings assigned to WWTFs, a fractional proportioning of remaining flow based on the area of the watershed under stormwater regulation, and assigning the remaining portion to unregulated stormwater.

4.4 Load Reduction Analysis

The TMDLs for the Navasota River and the impaired tributaries were developed using LDCs and associated load allocations using a load reduction analysis. Necessary load reduction to meet allowable loading within each segment using historical bacteria data were calculated by subtracting the TMDL from the current load thus yielding the needed level of reduction. Percent reductions were calculated from these same numbers (Table 17~~Table 17~~).

4.5 Margin of Safety

The Margin of Safety (MOS) must be included when developing a TMDL to account for uncertainty between the model and the environment. The MOS is determined by quantifying uncertainty to the extent possible. The MOS can be integrated into the TMDL with the two methods set by the USEPA:

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.

Including the MOS in the TMDL will support a higher levels of assurance the TMDL goal will be met. The TMDL in this report incorporates an explicit MOS of 5%.

Table 17. Load reduction analysis on all impaired segments in the Navasota watershed.

Station ID	AU ID	Reduction Needed	High Flows	Moist Conditions	Mid-Range Flows	Dry Conditions	Lowest Flows
16398	1209_03	Load	1.62E+13	2.77E+11	NA	NA	NA
		Percent	79	28	NA	NA	NA
11877	1209_05	Load	1.63E+14	NA	NA	NA	NA
		Percent	89	NA	NA	NA	NA
11789	1209E	Load	4.47E+13	1.25E+12	4.78E+11	9.66E+10	NA
		Percent	95	81	71	61	NA
16389	1209H_01	Load	5.45E+12	4.72E+11	1.31E+11	7.88E+9	8.78E+8
		Percent	82	61	50	36	44
16390	1209H_02	Load	4.91E+12	2.57E+10	1.07E+9	4.54E+9	8.13E+7
		Percent	85	16	14	29	4
11756	1209I_01	Load	2.51E+13	1.36E+12	6.66E+11	NA	1.36E+10
		Percent	86	58	59	NA	49
18800	1209I_02	Load	NA	1.56E+12	2.67E+10	480E+10	1.70E+10
		Percent	NA	68	9	46	72
11790	1209J	Load	1.03E+11	1.84E+11	1.49E+12	827E+9	NA
		Percent	50	67	96	31	NA
16384	1209K	Load	1.23E+14	3.25E+11	1.51E+11	198E+10	NA
		Percent	98	52	52	22	NA

4.6 Pollutant Load Allocation

A TMDL serves as the maximum amount of pollutant a water body can receive in a single day without surpassing the water quality standard. The total maximum daily load was calculated using Equation 5 below:

$$TMDL = WLA + LA + FG + MOS \qquad \text{(Eq. 5)}$$

Where:

TMDL = total maximum daily load

WLA = wasteload allocation, the amount of pollutant allowed by existing regulated or permitted dischargers

LA = load allocation, the amount of pollutant allowed by non-regulated or non-permitted sources

FG = loadings associated with future growth from potential permitted facilities

MOS = margin of safety

TMDLs may be expressed as mass per time, toxicity, or other relevant measures. TMDLs for *E. coli* are expressed as MPN/day.

The TMDL for the impaired assessment units within the report are determined using median streamflow within the high flow regime (5% flow). For the remainder of the report, each section will present will discuss the component, the explanation, and the results of the component of the TMDL.

4.6.1 AU-Level TMDL Computations

Bacteria TMDLs for the Navasota River below Lake Limestone were developed based on the LDC information as pollutant load allocations. As discussed, LDCs for bacteria were developed by multiplying each flow value by the *E. coli* criterion (126 MPN/100mL) and by the conversion factor used to represent maximum loading in MPN/day. Allowable load is displayed in the LDC at 5% exceedance (the median of the high flow regime) and is the TMDL (Eq. 6). Values of allowable loadings within the Navasota are shown in Table 18~~Table 18~~.

TMDL (MPN/day) = Criterion * Flow (cfs) * Conversion factor (Eq. 6)

Where:

Criterion = 126 MPN/100 mL (*E. coli*)

Conversion factor (MPN/day) = 28316.846 mL/ft3 * 86,400 sec/day = 24,465,755.4624 MPN/day

Table 18. Allowable loadings in impaired segments of the Navasota River watershed.

Station ID	Name	AU ID	5% Exceedance Flow (cfs)	5% Exceedance Load (MPN/day)	Indicator Bacteria	TMDL (Billion MPN/day)
16398	Nav at Grimes	1209_03	3,595.74	1.11E+13	*E. coli*	11,100
11877	Nav at US 79	1209_05	1,135.59	3.50E+12	*E. coli*	3,500
11789	Wickson Cr	1209E	205.48	6.33E+11	*E. coli*	633
16389	Duck SH79	1209H_01	178.38	5.49E+11	*E. coli*	549
16390	Duck FM 979	1209H_02	146.59	4.51E+11	*E. coli*	451
11756	Gibbon Cr	1209I_01	1192.7	3.67E+12	*E. coli*	3,670
18800	Gibbon Cr	1209I_02	502.23	1.55E+12	*E. coli*	1,550
11790	Shepherd Cr	1209J	32.51	1.00E+11	*E. coli*	100
16384	Steele Cr	1209K	371.40	1.14E+12	*E. coli*	1,140

4.6.2 Margin of Safety

The margin of safety is applied to the allowable load in the watershed. Equation 7 was used to calculate the MOS for impaired AUs in the Navasota River watershed (Table 19~~Table 19~~).

MOS = 0.05 * TMDL (Eq. 7)

Where:

MOS = margin of safety load

TMDL = total maximum allowable load

Table 19. Margin of safety calculations for the Navasota watershed below Lake Limestone.

Station ID	Name	AU ID	TMDL (Billion MPN/day)	Indicator Bacteria	MOS (Billion MPN/day)
16398	Nav at Grimes	1209_03	11,100	*E. coli*	554
11877	Nav at US 79	1209_05	3,500	*E. coli*	175
11789	Wickson Cr	1209E	633	*E. coli*	31.6
16389	Duck Cr	1209H_01	549	*E. coli*	27.5
16390	Duck Cr	1209H_02	451	*E. coli*	22.6
11756	Gibbon Cr	1209I_01	3,670	*E. coli*	183
18800	Gibbon Cr	1209I_02	1,550	*E. coli*	77.4
11790	Shepherd Cr	1209J	100	*E. coli*	50.1
16384	Steele Cr	1209K	1,140	*E. coli*	57.2

4.6.3 Wasteload Allocation

Wasteload allocation is the total sum of loads from regulated sources (Eq. 8). It is the wasteload allocated to TPDES regulated discharges and the waste load that is allocated to stormwater discharge. Wasteload allocation is based on the equation below where WLA_{WWTF} is the regulated wastewater treatment facility loading and WLA_{SW} is the regulated stormwater discharge.

$$WLA = WLA_{WWTF} + WLA_{SW} \quad \text{(Eq. 8)}$$

TPDES regulated discharges are allowed a daily waste load determined as their full permitted discharge flow rate multiplied by the instream geometric criterion (Eq. 9).

$$WLA_{WWTF} = Criterion * Flow * Conversion\ Factor \quad \text{(Eq. 9)}$$

Where:

Criterion= 126 MPN/100 mL for *E. coli*
Flow = full permitted flow (MGD)
Conversion Factor (to MPN/day) = 1.54723 cfs/MGD *28316.846 mL/ft3 * 86,400 sec/day

Daily allowable loading of *E.coli* for WLA_{WWTF} was determined by the full permitted discharge from each WWTF using the above equation.

Table 20Table 20 shows the wastewater treatment facilities within the TMDL watershed.

Table 20. Wasteload allocations for the TPDES permitted facilities within the Navasota watershed.

AU	TPDES Permit No.	Facility	Receiving Waters	Final Permitted Discharges (MGD) [a]	*E. coli* WLA_{WWTF} (Billion MPN/ day) [b]
1209	WQ0013931001	CITY OF ANDERSON: WWTF	To an unnamed tributary, thence to Holland Creek and to the Navasota River Below Lake Limestone in Segment 1209 of the Brazos River Basin	0.065	.310
1209C	WQ0010426001	CITY OF BRYAN: Burton Creek WWTF	To an unnamed tributary, then to Burton Creek, Carter's Creek and then to the Navasota River Below Lake Limestone	8.0	38.157
1209C	WQ0013153001	CITY OF COLLEGE STATION: Carter Lake WWTF	To an unnamed tributary of Carters Creek, then to Carters Creek and to Navasota River Below Lake Limestone	0.0085	.041
1209	WQ0010024003	CITY OF COLLEGE STATION: Lick Creek WWTF	To Alum Creek, then to Lick Creek and to Navasota River Below Lake Limestone	2.0	9.539
1209C	WQ0010024006	CITY OF COLLEGE STATION: Carters Creek WWTF	To Carters Creek and then to the Navasota River Below Lake Limestone	9.5	45.311
1209	WQ0013980001	CITY OF MARQUEZ: WWTF	To an unnamed tributary, then to Brushy Creek and to the Navasota River below Lake Limestone	0.04	.191
1209K	WQ0010824001	CITY OF THORNTON: WWTF	To an unnamed tributary, then to Steele Creek and to the Navasota River Below Lake Limestone	0.041	.196
1209C	WQ0012296001	R&B MOBILE PARK LLC DBA GLEN OAKS MOBILE HOME PARK	To an unnamed tributary, to Carters Creek and then to the Navasota River Below Lake Limestone	0.013	.062
Navasota River Watershed Total					93.807

[a] Permitted Flow from **Error! Reference source not found.**~~Table 5~~

[b] WLA_{WWTF} = Criterion * Flow * Conversion Factor (Eq. 9)

Stormwater discharges from MS4, industrial, and construction areas are considered regulated point sources. Therefore, WLA calculations must also include allocations for permitted stormwater discharges (WLA_{SW}). A simplified approach for estimating the WLA for these areas was used in the development of this TMDL due to the limited amount of data available, the complexities associated with simulating rainfall runoff, and variability in stormwater loading. The 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}. To accomplish this, the area of the watershed where permitted stormwater is generated is used to estimate the amount of the overall runoff load that should be allocated as permitted stormwater contribution in the WLA_{SW} component of the TMDL. Table 21~~Table 21~~ shows the permitted areas for the different permits and the final fractional proportion of drainage area. WLA_{SW} is the sum of loads from regulated stormwater sources and is calculated as follows (Equation 10):

$$WLA_{SW} = (TMDL - WLA_{WWTF} - FG - MOS) * FDA_{SW} \quad \text{(Eq. 10)}$$

Where:

WLA_{SW} = sum of all regulated stormwater loads

TMDL = total maximum daily load

WLA_{WWTF} = sum of all WWTF loads

FG = sum of future growth loads from potential permitted facilities

MOS = margin of safety load

FDA_{SWP} = fractional proportion of drainage area under jurisdiction of stormwater permits

Table 21. Regulated stormwater calculations for the Navasota watershed.

AU	Station ID	MS4 General Permit (acres)	Multi-sector General Permit (acres)	Construction Activities (acres)	Concrete Production Facilities (acres)	Petroleum Bulk Stations (acres)	Total	Watershed Area (acres)	FDA_{SWP}
1209_03	16398	0	8,357.47	1,258.6	0	0	9,616.07	719,434.2	0.00414
1209_05	11877	0	4,589.6	520.2	0	0	5,109.8	227,062	0.02250
1209E	11789	0	326.87	184	0	0	510.87	56,401	0.00906
1209H_01	16389	0	0	66	0	0	66	96,276	0.00069
1209H_02	16390	0	880	53	0	0	933	48,138	0.01938
1209I_02	18800	0	515	12.6	0	0	527.6	75,763	0.00696
1209I_01	11756	0	0	0	0	0	0	37,881.5	0.00000
1209J	11790	0	0	15.4	0	0	15.4	16,709	0.00092
1209K	16384	0	2561	420	0	0	2981	118,721	0.02511

To calculate WLA_{SW}, the Future Growth (FG) variable must be known. The equation and calculations are shown in the next section, however, results are included below in Table 22~~Table 22~~ for continuity.

Table 22. Regulated stormwater calculations (MPN/day) for the Navasota watershed.

AU ID	TMDL [a]	WLA_{WWTF} [b]	FG [c]	MOS [d]	FDASWP	WLA_{SW} [f]
1209_03	11100	0.38655422	8.96506	554	0.00414	43.65896
1209_05	3500	0.38655422	1.126948	175	0.02250	74.79169
1209E	633	0	4.389026	31.6	0.00906	5.407617
1209H_01	549	0	0.658857	27.5	0.00069	0.357052
1209H_02	451	0	0.070085	22.6	0.01938	8.301795
1209I_01	3670	0	0.371344	183	0.00696	24.28026
1209I_02	1550	0	0.234437	74.4	0.00000	0
1209J	100	0	0.173137	50.1	0.00092	0.045831
1209K	1140	0.19555422	0.066489	57.2	0.02511	27.18176

[a] TMDL from Table 18. Allowable loadings in impaired segments of the Navasota River watershed.~~Table 18.~~

[b] **WLA_{WWTF} from**

Table **20. Wasteload allocations for the TPDES permitted facilities within the Navasota watershed.~~Table 20.~~**

[c] FG from Table 23. Future growth of current WWTFs in the Navasota watershed. Table 24~~Table 24.~~

[d] MOS from Table 19. Margin of safety calculations for the Navasota watershed below Lake Limestone.~~Table 19.~~

[e] FDA_{SWP} from Table 21. Regulated stormwater calculations for the Navasota watershed.~~Table 21.~~

[f] WLA_{SW} = (TMDL – WLA_{WWTF} – FG – MOS) * FDA_{SWP}

4.6.4 Future Growth

Future growth is a component of the TMDL that accounts for future population growth and changes in infrastructure and development. Increases in flow allow for additional bacterial loads if the concentrations are at or below the set recreational standards.

Currently, there are eight WWTFs in the watershed but only two of them directly affect the impaired segments in the watershed (Table 23~~Table 23~~). The City of Thornton WWTF is located in Limestone County and is within the Steele Creek subbasin. Steele Creek flows into 1209_05 of the Navasota River. The City of Marquez is located in Leon County and its WWTF contributes flow to Navasota River AU 1209_05. Together, these contributions also impact Navasota River AU 1209_03 downstream. Projected population growth for Limestone and Leon County between the years of 2020 to 2070 was previously found in Table 2~~Table 2~~. The calculation results for the impaired AU segments are shown in

Table 20~~Table 20~~.

$$FG = Criterion * [\%POP_{2020\text{-}2070} * WWTF_{FP}] * Conversion\ Factor \qquad \text{(Eq. 11)}$$

Where:

Criterion = 126 MPN/100 mL for *E. coli*

$\%POP_{2020\text{-}2070}$ = estimated % increase in population between 2020 and 2070

$WWTF_{FP}$ = full permitted discharge (MGD)

Conversion Factor (to MPN/day) = 1.54723 cfs/MGD *28316.846 mL/ft3 * 86,400 sec/day

Table 23. Future growth of current WWTFs in the Navasota watershed.

TPDES Permit No.	Facility	Full Permitted Flow (MGD)	Type/ Location of Outfall	% Population Increase (2020-2070)	2070 Permitted Flow (Future Growth) (MGD)[a]	FG E. coli (Billion MPN/ day) [b]
WQ0013980001	CITY OF MARQUEZ: WWTF	0.04	Municipal/Leon	47%	0.019	0.0897
WQ0010824001	CITY OF THORNTON: WWTF	0.041	Municipal/Limestone	34%	0.014	0.0665
Navasota Watershed Total					0.03274	0.1561572

[a] Significant digits based on full permitted flow

[b] $FG = Criterion * [\%POP_{2010\text{-}2050} * WWTF_{FP}] * Conversion\ Factor$ (Eq. 11)

There are segments within the Navasota basin that do not currently have a wastewater treatment facility in them. This causes a shortcoming within the TMDL calculations because it does not consider future growth or future construction of a WWTF. While there are no current plans for any WWTFs to be built within the watershed, the TMDL must still account for the possibility of one being built in the future by calculating future growth for all impaired segments.

Rule §217.32 of Texas Administrative Code states that a new WWTF must be designed for a wastewater flow of 75-100 gallons per capita per day (gpcd; TAC, 2008). To know the full permit discharge for a given county, the county population was multiplied 100 gallons per capita per day and then converted into MGD. 100 gallons per capita per day was chosen, as it is the most conservative value. This full permit discharge can then be multiplied by the population growth percent and would be considered the full permitted discharge of a potential future WWTF.

The population was calculated for each subbasin of the impaired stream using US census block data. If population block data was located on the subbasin border, a percentage based approximation of the population was taken for that particular land parcel. Additionally, the population was not calculated for the northernmost subbasins as both already have WWTFs located within their borders and so future growth was already calculated. The information from Table 23~~Table 23~~ was utilized for Steele Creek and the Navasota River segments.

Since the main channel is in contact with more than one county, a weighted average of the population in the watershed area and the county growth population increase (Table 2~~Table 2~~) was used to calculate the population increase. Table 24Table 24 shows the impaired segment, the current population, and the regulated code used to calculate permitted flow for a possible future WWTF. Using the Equation 11, future growth was calculated.

Table 24. Future growth for current and future WWTFs in the Navasota watershed.

AU ID	Current County Population	Regulated Code	Permitted Flow (MGD)	Type/ Location of Outfall	% Population Increase (2020-2070)	2070 Permitted Flow (Future Growth) (MGD)[a]	E. coli FG (Billion MPN/ day) [b]
1209_03	20,514	100	2.5113	City of Marquez and Thornton/Future/ Leon and Limestone	75%	1.880	8.965
1209_05	4,189	100	0.4599	City of Marquez and Thornton/ Leon	51%	0.236	1.127
1209E	7,421	100	0.7421	Future/ Brazos	124%	0.920	4.389
1209H_01	2,228	100	0.2228	Future/ Robertson	62%	0.138	0.659
1209H_02	237	100	0.0237	Future/ Robertson	62%	0.015	0.070
1209I_01	1,622	100	0.1622	Future/Grimes	48%	0.078	0.371
1209I_02	1,024	100	0.1024	Future/Grimes	48%	0.049	0.234
1209J	825	100	0.0825	Future/Madison	44%	0.036	0.173
1209K	N/A	N/A	0.041	City of Thornton/Limestone	34%	0.014	0.066
Navasota Watershed Total						3.366	16.055

4.6.5 Load Allocation

The load allocation (LA) is the loading from unregulated sources. It was calculated from Equation 12 and summarized in Table 25Table 25.

$$LA = TMDL - WLA_{WWTF} - WLA_{SW} - FG - MOS \qquad (Eq.\ 12)$$

Where:

LA = allowable loads from unregulated sources within the AU

TMDL = total maximum daily load

WLA_{WWTF} = sum of all WWTF loads

WLA_{SW} = sum of all regulated stormwater loads

FG = sum of future growth loads from potential permitted facilities

MOS = margin of safety load

Table 25. Load allocations (MPN/day) for the Navasota watershed.

All loads expressed as Billion MPN/day

AU ID	TMDL [a]	WLA_{WWTF} [b]	WLA_{SW} [c]	FG [d]	MOS [e]	LA [f]
1209_03	11,100	0.386554221	43.69771	8.96506	554	10,492.9507
1209_05	3,500	0.386554221	74.80676	1.126948	175	3,248.67974
1209E	633	0	5.447372	4.389026	31.6	591.563602
1209H_01	549	0	0.357503	0.658857	27.5	520.48364
1209H_02	451	0	8.303153	0.070085	22.6	420.026762
1209I_01	3,670	0	24.28285	0.371344	183	3,462.34581
1209I_02	1,550	0	0	0.234437	74.4	1,475.36556
1209J	100	0	0.045991	0.173137	50.1	49.6808719
1209K	1,140	0.195554221	27.18156	0.066489	57.2	1,055.3564

[a] TMDL from Table 18. Allowable loadings in impaired segments of the Navasota River watershed.~~Table 18.~~

[b] WLA_{WWTF} from

Table **20. Wasteload allocations for the TPDES permitted facilities within the Navasota watershed.~~Table 20.~~**

[c] WLA_{SW} = (TMDL – WLA_{WWTF} – FG – MOS) * FDA_{SWP}

[d] FG from Table 23. Future growth of current WWTFs in the Navasota watershed. ~~Table 23.~~

[e] MOS from Table 19. Margin of safety calculations for the Navasota watershed below Lake Limestone.~~Table 19.~~

[f] LA = TMDL – WLA_{WWTF} - WLA_{SW} - FG – MOS (Eq. 12)

4.7 Summary of TMDL Calculations

Table 26~~Table 26~~ summarizes the TMDL calculations for the Navasota River and its tributaries. The TMDL was calculated based on the median percentile range (5% exceedance) in the high flow regime from the LDC developed for each impaired segment. Allocations are based on geometric mean criterion for *E.coli* of 126 MPN/day and include a 5% explicit MOS.

Table 26. Final TMDL allocation summary (MPN/day) for the Navasota watershed.

All loads expressed as Billion MPN/day

AU ID	TMDL [a]	MOS [b]	WLA_{WWTF} [c]	WLA_{SW} [d]	LA [e]	FG [f]
1209_03	11,100	554	0.386554221	43.7	10,493.052	8.965
1209_05	3,500	175	0.386554221	74.81	3,248.781	1.127
1209E	633	31.6	0	5.45	591.564	4.389
1209H_01	549	27.5	0	0.36	520.484	0.659
1209H_02	451	22.6	0	8.3	420.027	0.07
1209I_01	3,670	183	0	24.28	3,462.346	0.371
1209I_02	1,550	74.4	0	0	1,475.366	0.234
1209J	100	50.1	0	0.05	49.681	0.173
1209K	1,140	57.2	0.195554221	27.18	1,055.356	0.066

[a] TMDL from Table 18. Allowable loadings in impaired segments of the Navasota River watershed.~~Table 18.~~

[b] MOS from Table 19. Margin of safety calculations for the Navasota watershed below Lake Limestone.~~Table 19.~~

[c] **WLA_{WWTF} from**

Table 20. Wasteload allocations for the TPDES permitted facilities within the Navasota watershed.Table 20.

[d] WLA_{SW} = (TMDL – WLA_{WWTF} – FG – MOS) * FDA_{SWP}

[e] LA = TMDL – WLA_{WWTF} - WLA_{SW} - FG – MOS (Eq. 12)

[f] FG from Table 23. Future growth of current WWTFs in the Navasota watershed. Table 24Table 24.

The final TMDL allocations comply with the requirements of 40 CFR 130.7 and include the future growth component within the WLA_{WWTF} (Table 27Table 27).

Table 27. Final TMDL allocations that comply with the requirements of 40. CR 130.7.
All loads expressed as Billion MPN/day

AU ID	TMDL [a]	WLA_{WWTF} [b]	WLA_{SW} [c]	LA [d]	MOS [e]
1209_03	11,100	9.351554221	43.7	10,493.052	554
1209_05	3,500	1.513554221	74.81	3,248.781	175
1209E	633	4.389	5.45	591.564	31.6
1209H_01	549	0.659	0.36	520.484	27.5
1209H_02	451	0.07	8.3	420.027	22.6
1209I_01	3,670	0.371	24.28	3,462.346	183
1209I_02	1,550	0.234	0	1,475.366	74.4
1209J	100	0.173	0.05	49.681	50.1
1209K	1,140	0.261554221	27.18	1,055.356	57.2

[a] TMDL from Table 18. Allowable loadings in impaired segments of the Navasota River watershed.Table 18.

[b] WLA_{WWTF} (Table 20Table 20) + FG (Table 24Table 24).

[c] WLA_{SW} = (TMDL – WLA_{WWTF} – FG – MOS) * FDA_{SWP}

[d] LA = TMDL – WLA_{WWTF} - WLA_{SW} - FG – MOS (Eq. 12)

[e] MOS from Table 19. Margin of safety calculations for the Navasota watershed below Lake Limestone.Table 19.

Appendix A provides guidance for recalculating allocations should the water quality criterion change in the future due to state water quality standards revisions.

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Appendix A. Equations for Calculating TMDL Allocations for Changed Contact Recreation Standard

In all cases, the following abbreviations apply for the presented equations:

Std =	Revised Contact Recreation Standard
MOS =	Margin of Safety
LA =	Total load allocation (non-permitted source contributions)
WLA_{WWTF} =	Wasteload allocation (permitted WWTF load + future growth) [Note: WWTF load held at Primary Contact (126 MPN/ 100 mL) criterion]
WLA_{SW} =	Wasteload allocation (permitted stormwater)

Table A- 1. Summary of allocation loads for Navasota River (AU 1209_03) at selected water quality standards.

STD (MPN/100 mL)	TMDL	MOS	LA	WLA_{wwtf}	WLA_{sw}
126	11084.52	554.2258	10486.31	0.386339	43.5938
630	55422.58	2771.129	52433.09	0.386339	217.9754
1030	90611.52	4530.576	85724.19	0.386339	356.3735

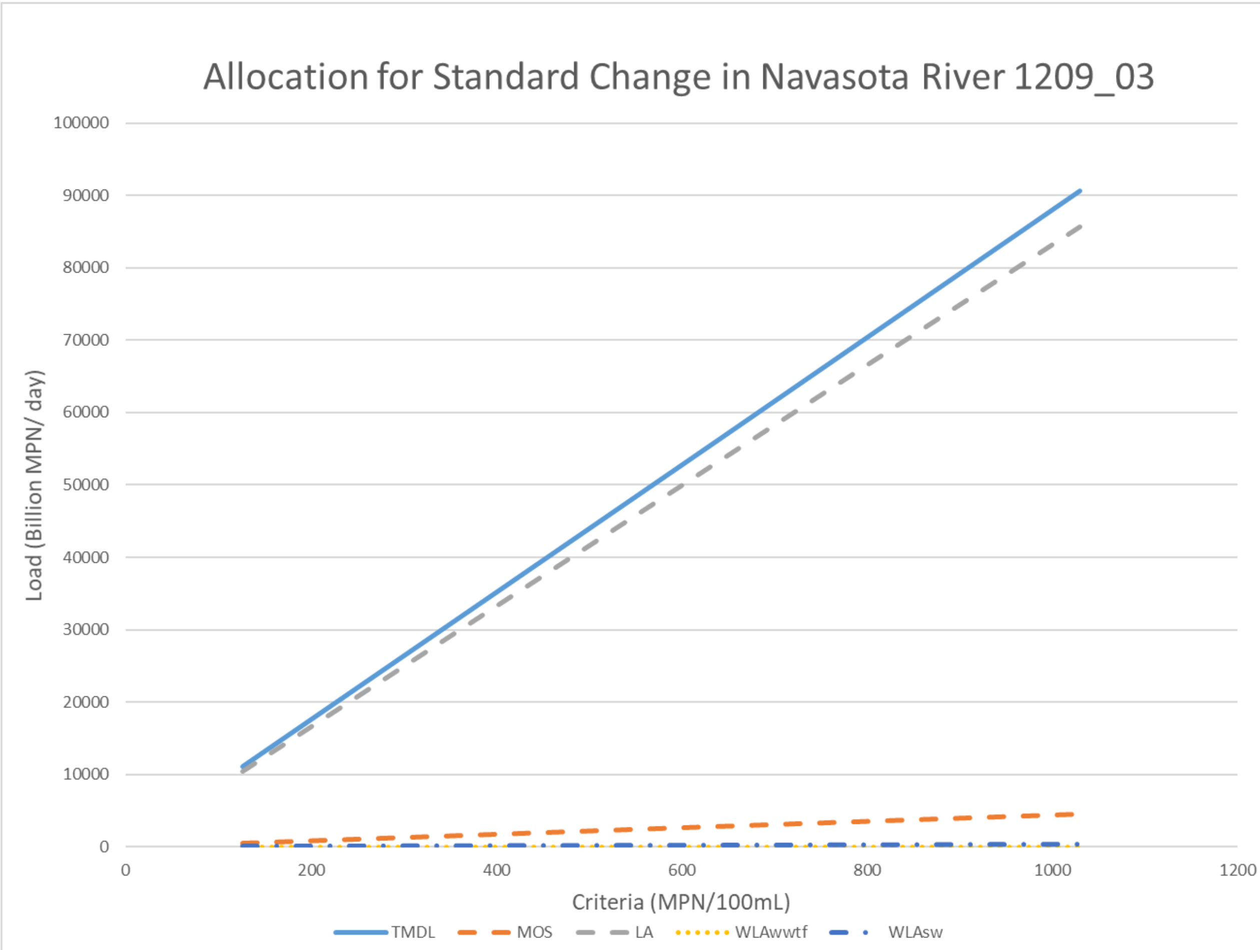

Figure A-1. Allocation loads for Navasota River (AU 1209_03) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209_03

TMDL	= 87.972351 * Std
MOS	= 4.398617539 * Std
LA	= 83.22773798 * Std - 0.365502416
WLA_{WWTF}	= .3670219
WLA_{SW}	= 0.34599526 * Std - 0.001519

Table A- 2. Summary of allocation loads for Navasota River (AU 1209_05) at selected water quality standards.

STD (MPN/100 mL)	TMDL	MOS	LA	WLA_{wwtf}	WLA_{sw}
126	3500.661	175.033	3250.423	0.386339	74.81793
630	17503.3	875.1652	16253.63	0.386339	374.1244
1030	28616.51	1430.826	26573.63	0.386339	611.6693

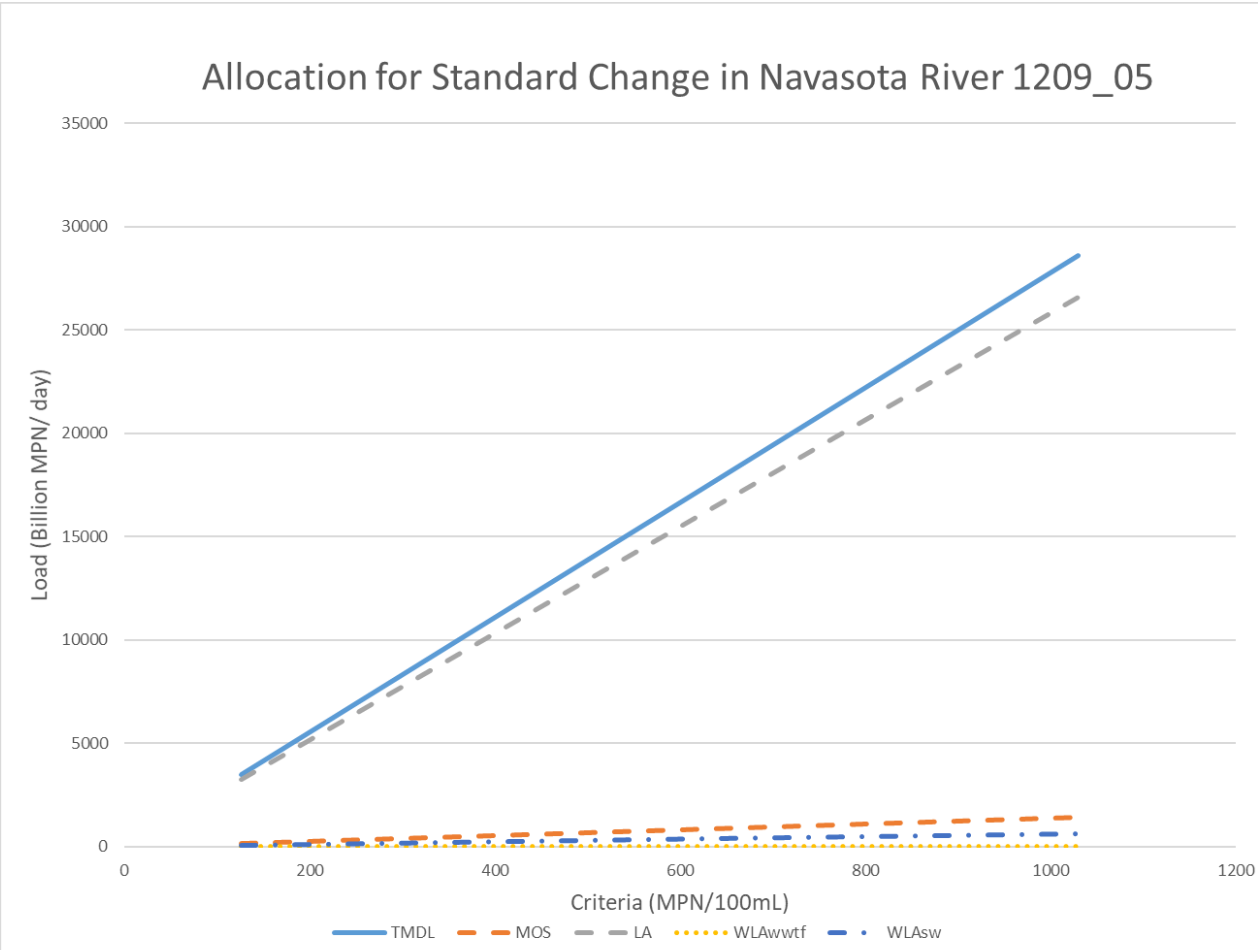

Figure A- 2. Allocation loads for Navasota River (AU 1209_05) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209_05

TMDL = 27.783022 * Std

MOS = 1.389151076 * Std

LA = 25.80000836 * Std - 0.358763894

WLA_{WWTF} = .367021886

WLA_{SW} = .59386209* Std - 0.0082580

Table A- 3. Summary of allocation loads for Wickson Creek (AU 1209E) at selected water quality standards.

STD(MPN/100 mL)	TMDL	MOS	LA	WLA_{WWTF}	WLA_{SW}
126	633.3366	31.66683	596.2187	0	5.451128
630	3,166.683	158.3342	2,981.093	0	27.25564
1030	5,177.276	258.8638	4,873.851	0	44.56081

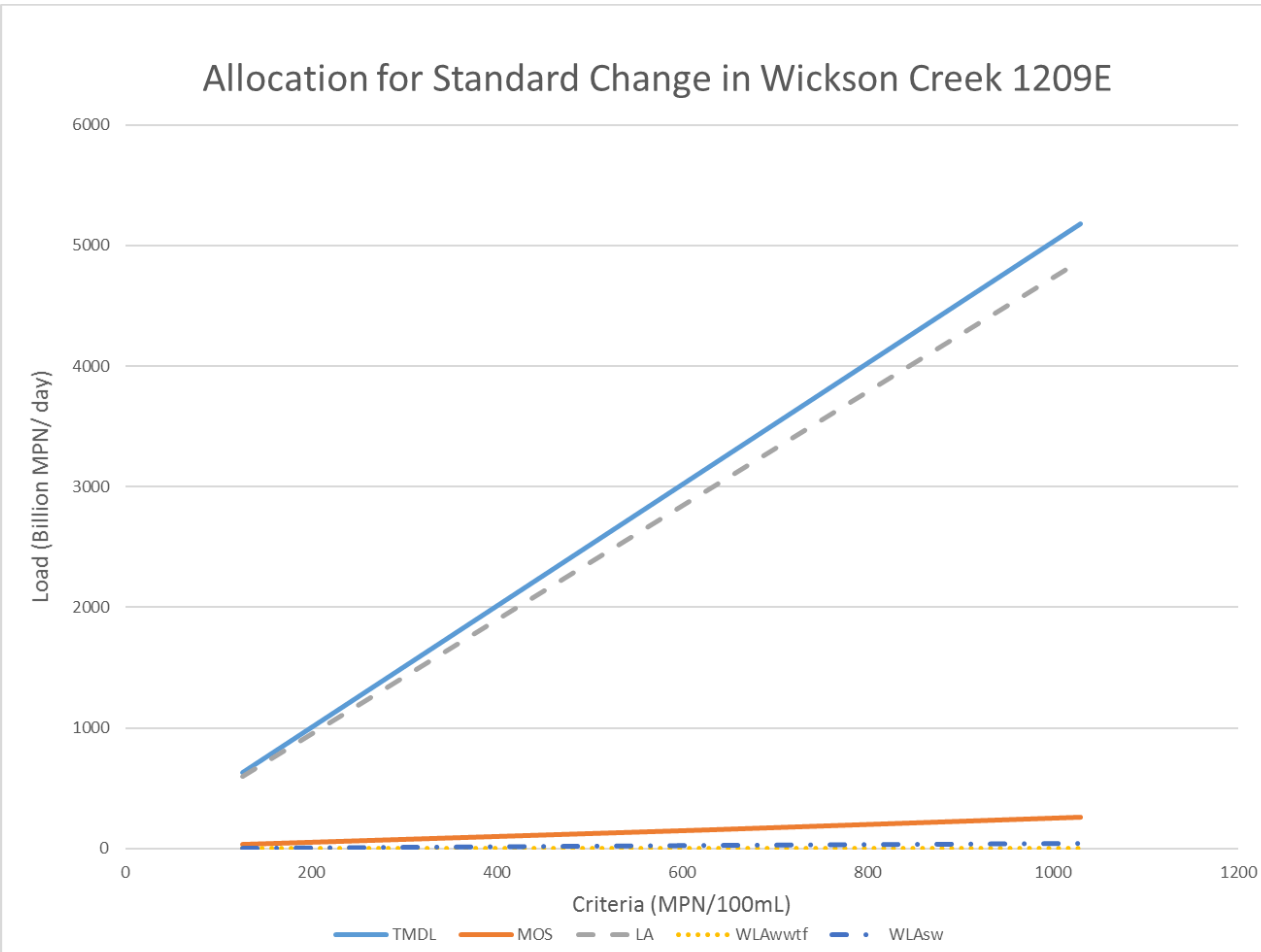

Figure A- 3. Allocation loads for Wickson Creek (AU 1209E) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209E

TMDL	= 5.0264812 * Std
MOS	= .251324059 * Std
LA	= 4.731894205 * Std
WLA_{WWTF}	= 0
WLA_{SW}	= .04326292 * Std

Table A- 4. Summary of allocation loads for Duck Creek (AU 1209H_01) at selected water quality standards.

STD (MPN/100 mL)	TMDL	MOS	LA	WLA_{WWTF}	WLA_{SW}
126	549.8885	27.49442	522.0336	0	0.360452
630	2,749.442	137.4721	2610.168	0	1.802259
1030	4,495.12	224.756	4,267.418	0	2.946551

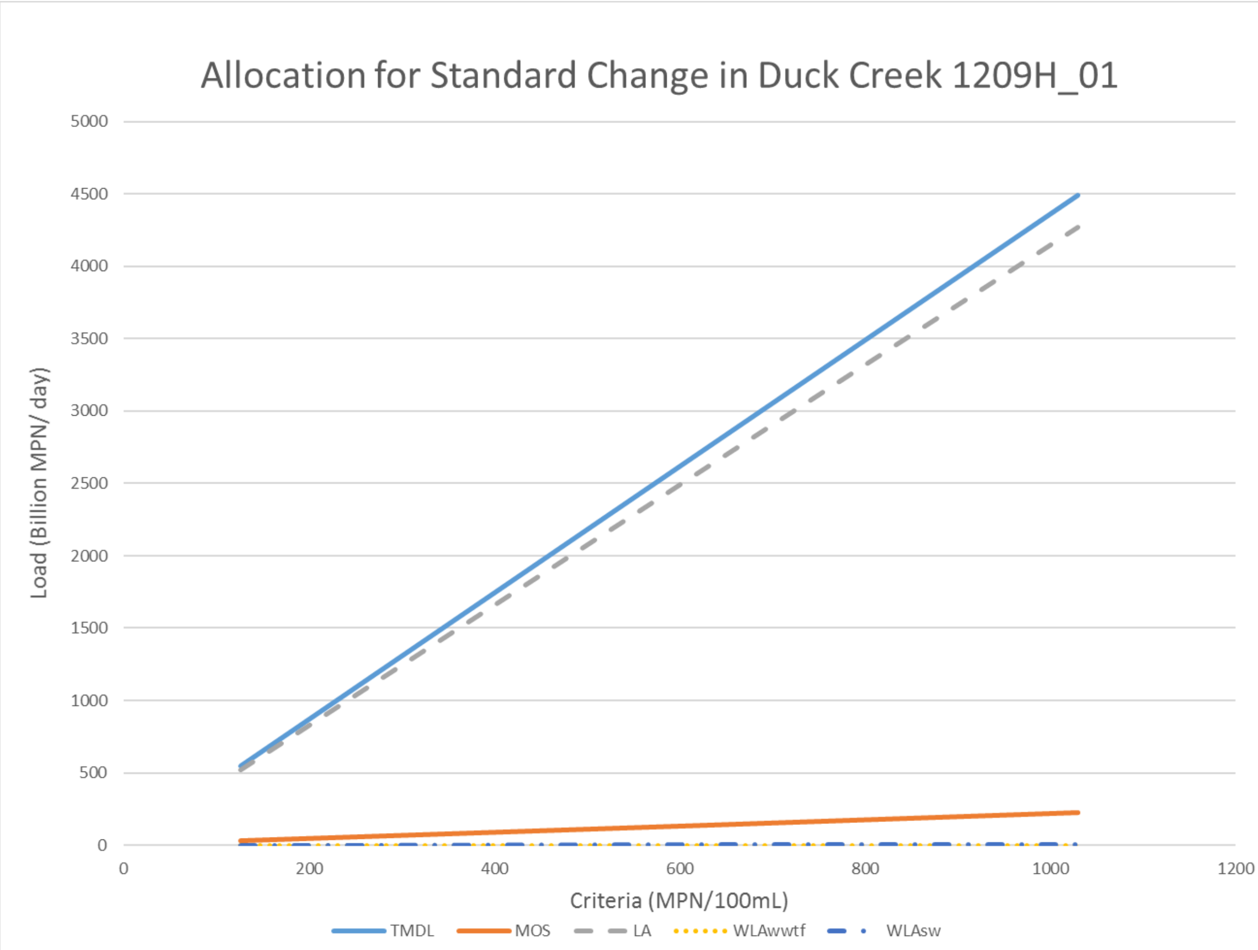

Figure A- 4. Allocation loads for Duck Creek (AU 1209H_01) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209H_01

TMDL	= 4.3641943 * Std
MOS	= .218209714 * Std
LA	= 4.143123834 * Std
WLA_{WWTF}	= 0
WLA_{SW}	= 0 * Std

Table A- 5. Summary of allocation loads for Duck Creek (AU 1209H_02) at selected water quality standards.

STD (MPN/100 mL)	TMDL	MOS	LA	WLA_{WWTF}	WLA_{SW}
126	451.8901	22.5945	420.9758	0	8.319748
630	2,259.45	112.9725	2,104.879	0	41.59874
1030	3,694.022	184.7011	3,441.31	0	68.01064

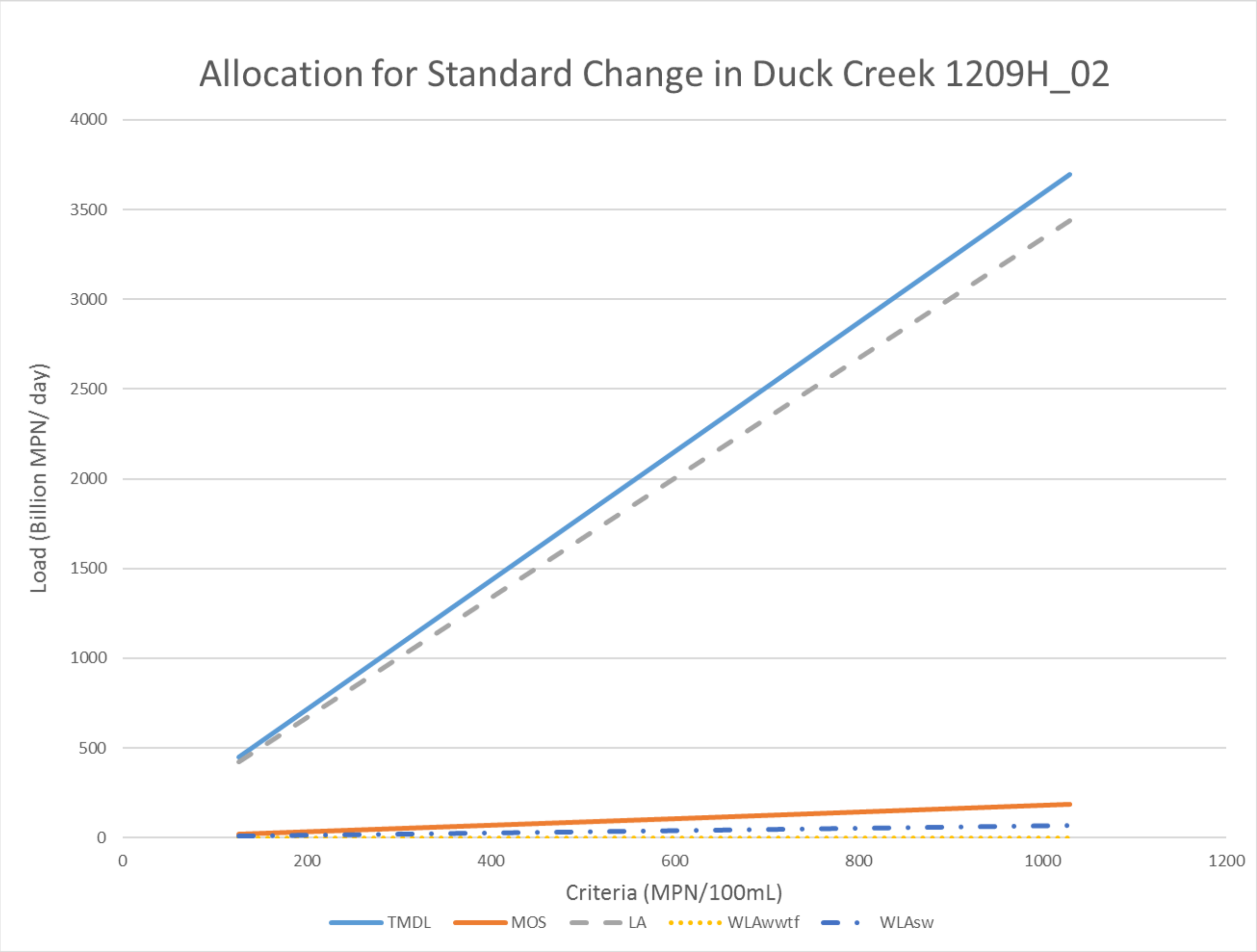

Figure A- 5. Allocation loads for Duck Creek (AU 1209H_02) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209H_02

TMDL	= 3.5864292 * Std
MOS	= 1..17932146 * Std
LA	= 3.341077984 * Std
WLA_{WWTF}	= 0
WLA_{SW}	= .06602975 * Std

Table A- 6. Summary of allocation loads for Gibbons Creek (AU 1209I_01) at selected water quality standards.

STD (MPN/100 mL)	TMDL	MOS	LA	WLA_{WWTF}	WLA_{SW}
126	3,676.713	183.8356	3,468.567	0	24.31042
630	18,383.56	919.1781	17,342.83	0	121.5521
1030	30,055.67	1,502.783	28,354.15	0	198.7281

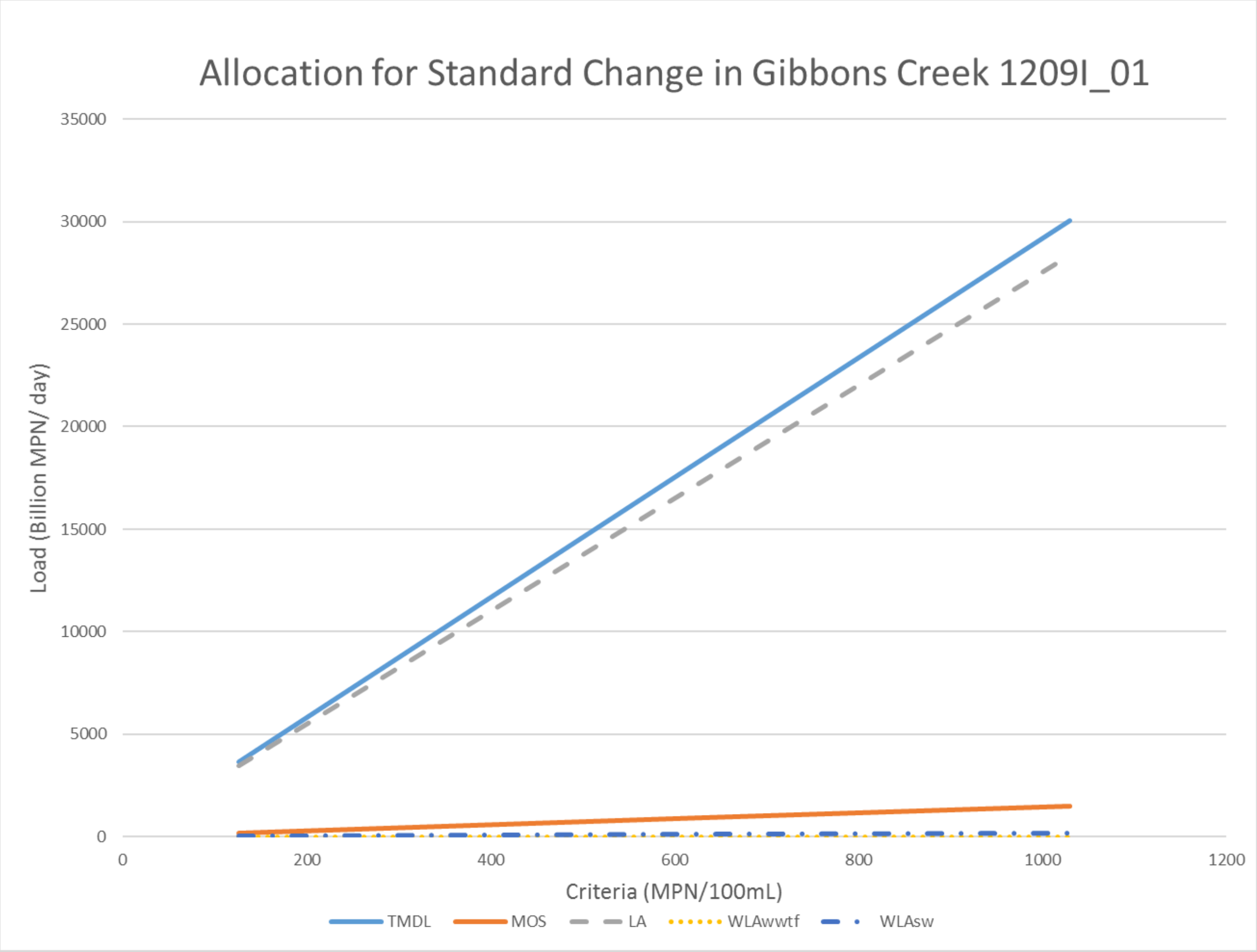

Figure A- 6. Allocation loads for Gibbon Creek (AU 1209I_01) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209I_01

TMDL	= 29.180259 * Std
MOS	= 1.459012926 * Std
LA	= 27.52830572 * Std
WLA_{WWTF}	= 0
WLA_{SW}	= .19293987 * Std

Table A- 7. Summary of allocation loads for Gibbons Creek (AU 1209I_02) at selected water quality standards.

STD (MPN/100 mL)	TMDL	MOS	LA	WLA_{WWTF}	WLA_{SW}
126	1,548.214	77.41072	1,470.804	0	0
630	7,741.072	387.0536	7,354.019	0	0
1030	12,656.04	632.8019	12,023.24	0	0

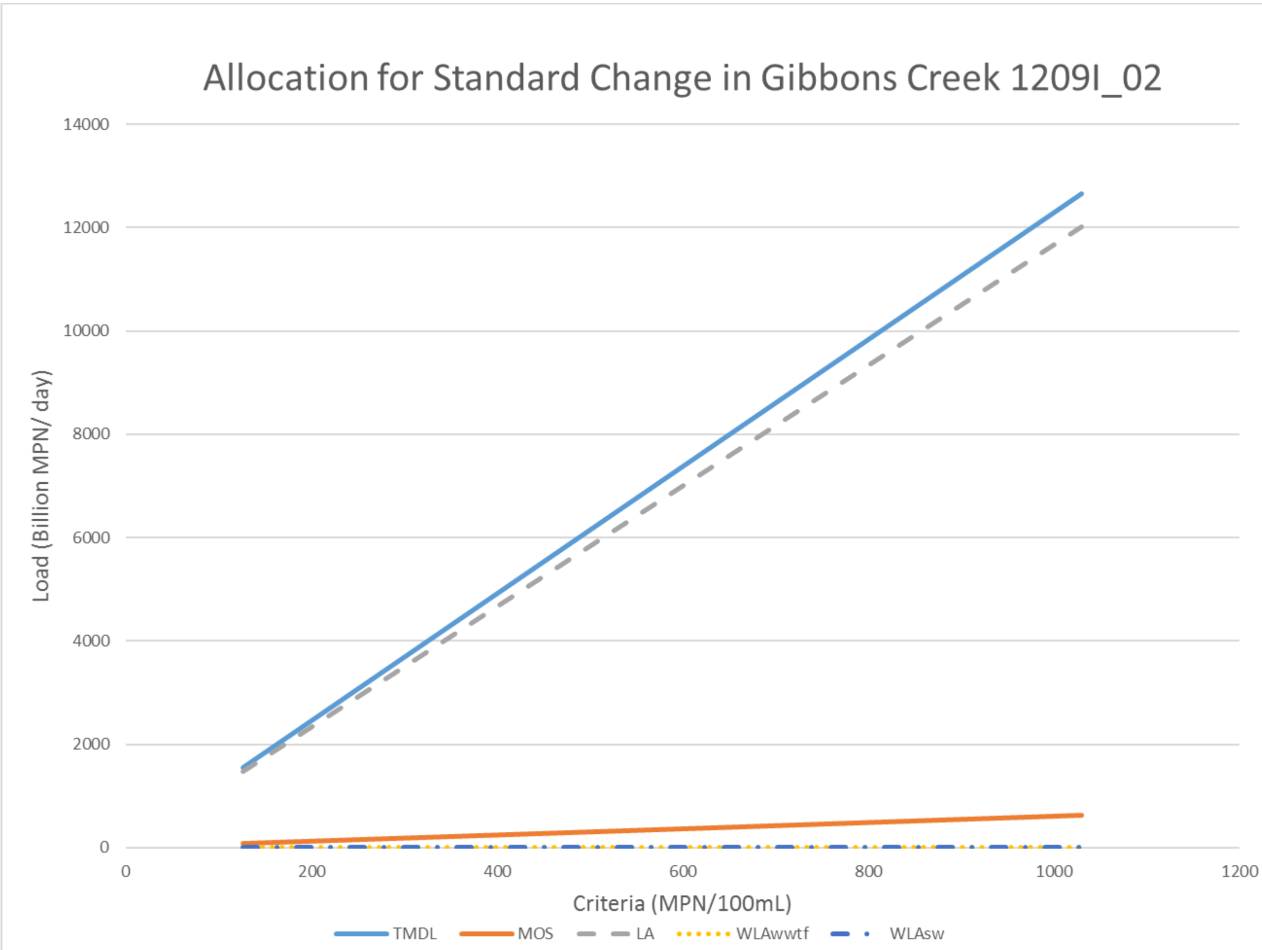

Figure A- 7. Allocation loads for Gibbon Creek (AU 1209I_02) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209I_02

TMDL	= 12.287416 * Std
MOS	= .614370807 * Std
LA	= 11.67304534 * Std
WLA_{WWTF}	= 0
WLA_{SW}	= 0 * Std

Table A- 8. Summary of allocation loads for Shepherd Creek (AU 1209J) at selected water quality standards.

STD (MPN/100 mL)	TMDL	MOS	LA	WLA_{WWTF}	WLA_{SW}
126	100.2179	5.010897	95.11944	0	0.08759
630	501.0897	25.05448	475.5972	0	0.437952
1030	819.2418	40.96209	777.5637	0	0.716017

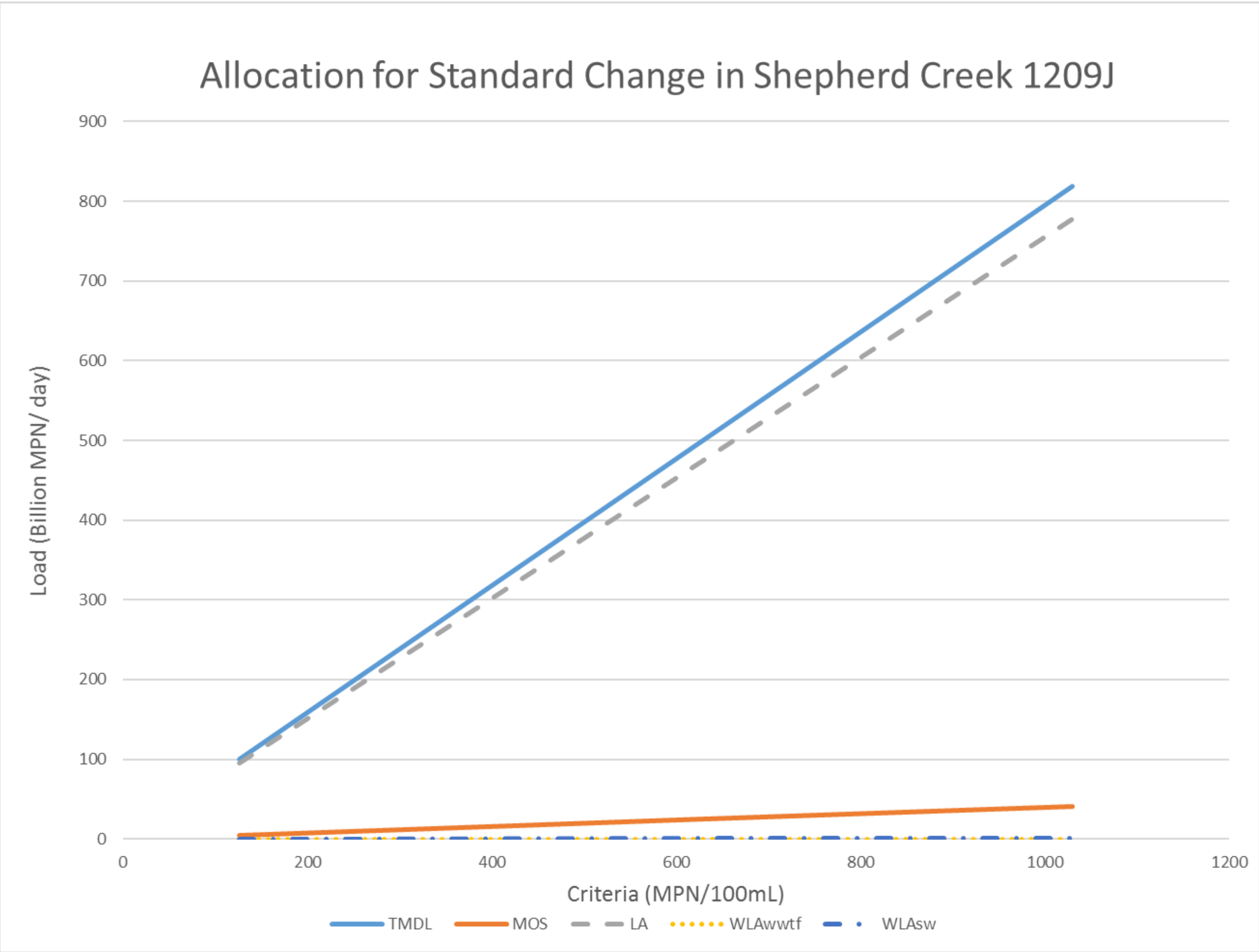

Figure A- 8. Allocation loads for Shepherd Creek (AU 1209J) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209J

TMDL = .7953804 * Std

MOS = .03976902 * Std

LA = .754916219 * Std

WLA_{WWTF} = 0

WLA_{SW} = 0 * Std

Table A- 9. Summary of allocation loads for Steele Creek (AU 1209K) at selected water quality standards.

STD (MPN/100 mL)	TMDL	MOS	LA	WLA_{WWTF}	WLA_{SW}
126	1,144.907	57.24537	1,060.351	0	27.31119
630	5,724.537	286.2268	5,301.754	0	136.556
1030	9,359.164	467.9582	8,667.947	0	223.2582

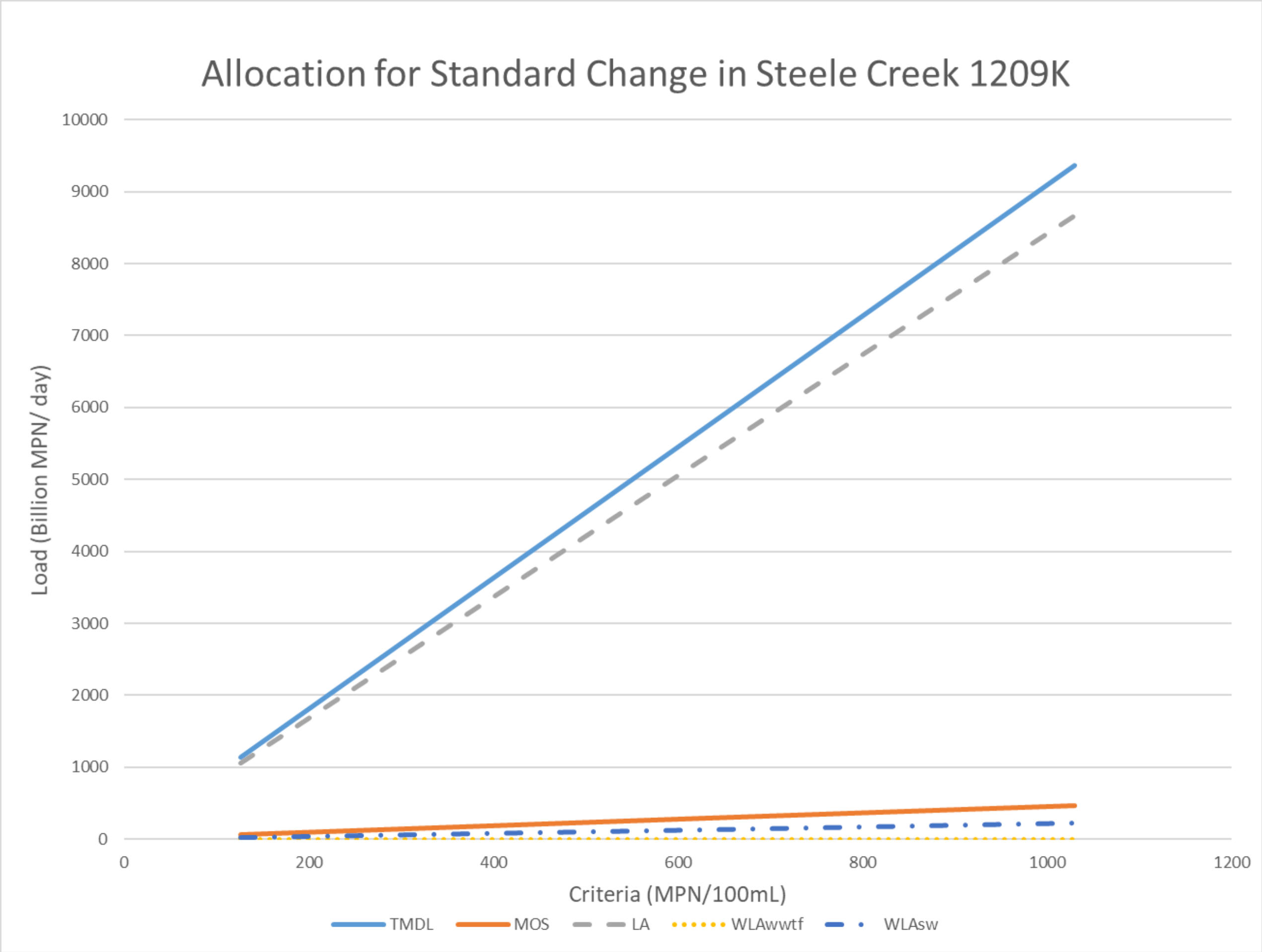

Figure A- 9. Allocation loads for Steele Creek (AU 1209K) as a function of water quality criteria.

Equations for calculating new TMDL and allocations (billion MPN/day) for 1209K

TMDL	= 9.086566 * Std
MOS	= .454328331 * Std
LA	= 8.41548279 * Std
WLA_{WWTF}	= 0.19955542
WLA_{SW}	= .21675550 * Std