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Two Total Maximum Daily Loads for Indicator Bacteria in the Navasota River below Lake Limestone

Segment 1209

Assessment Units 1209_03 and 1209_05

Water Quality Planning Division, Office of Water
TEXAS COMMISSION ON ENVIRONMENTAL QUALITY

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"Technical Support Document for Total Maximum Daily Loads for Indicator Bacteria in the Navasota River Watershed"
prepared by the Texas Water Resources Institute

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Abbreviations

95PPU	95 percent prediction uncertainty
ac	acres
AU	assessment unit
AVMA	American Veterinary Medicine Association
BMP	best management practice
CAFO	concentrated animal feeding operation
CFR	Code of Federal Regulations
cfs	cubic feet per second
DEM	digital elevation model
E. coli	*Escherichia coli*
EPA	United States Environmental Protection Agency
ET	evapotranspiration
FDA	fractional drainage area
FDC	flow duration curve
FG	future growth
GIS	geographic information system
HRU	hydrologic response unit
I&I	inflow and infiltration
I-Plan	implementation plan
LA	load allocation
LDC	load duration curve
MCM	minimum control measures
MGD	million gallons per day
mL	milliliter
MOS	margin of safety
MPN	most probable number
MS4	municipal separate storm sewer system
NLCD	National Land Cover Database
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
NSE	Nash Sutcliffe coefficient
OSSF	on-site sewage facility
PET	potential evapotranspiration
RUAA	recreational use attainability analysis
SSO	sanitary sewer overflow
SSURGO	Soil Survey Geographic
SUFI-2	Sequential Uncertainty Fitting 2
SWAT	Soil & Water Assessment Tool
SWAT-CUP	Soil & Water Assessment Tool-Calibration and Uncertainty Programs
SWMP	Stormwater Management Program
TCEQ	Texas Commission on Environmental Quality
TMDL	total maximum daily load

TPDES	Texas Pollutant Discharge Elimination System
TPWD	Texas Parks and Wildlife Department
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
USGS	United States Geological Survey
WLA	wasteload allocation
WQBEL	water quality-based effluent limits
WQMP	Water Quality Management Plan
WWTF	wastewater treatment facility

Two TMDLs for Indicator Bacteria in the Navasota River below Lake Limestone

Executive Summary

This document describes total maximum daily loads (TMDLs) for Navasota River below Lake Limestone where concentrations of indicator bacteria exceed the criteria used to evaluate attainment of the contact recreation use standard. The Texas Commission on Environmental Quality (TCEQ) first identified the impairments to the Navasota River below Lake Limestone [Segment 1209, assessment units (AUs) 1209_03 and 1209_05] in the *2002 Texas Integrated Report of Surface Water Quality for Clean Water Sections 305(b) and 303(d)* (Texas Integrated Report).

The Navasota River below Lake Limestone watershed is located in East-Central Texas and contains parts of six counties including Brazos, Grimes, Leon, Limestone, Madison, and Robertson. The Navasota River below Lake Limestone 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 river is a perennial freshwater stream, but the operations of Lake Limestone strongly influence its flows.

Escherichia coli (*E. coli*) are widely used as indicator bacteria to assess attainment of the contact recreation use in freshwater bodies. The criteria for assessing attainment of the contact recreation use are expressed as the number (or "counts") of *E. coli* bacteria, typically given as the most probable number (MPN) but also referred to as colony forming units. The primary contact recreation use is not supported when the geometric mean of all *E. coli* samples collected during the assessment period exceeds 126 MPN per 100 milliliters (mL).

Six tributary streams to the Navasota River below Lake Limestone that were impaired on the 2008 Texas Integrated Report were subject to a recreational use attainability analysis (RUAA) to determine the appropriate category of recreational use for each water body. The RUAA analysis resulted in a standards change recommendation for all six streams. The United States Environmental Protection Agency (EPA) approved a new recreational use category for two of the streams in 2018. EPA action is pending for the other four streams.

Three other tributaries of the Navasota River below Lake Limestone also have elevated *E. coli* concentrations. In 2012, TMDLs for bacteria in Carters Creek

(1209C), Burton Creek (1209L), and Country Club Branch (1209D) were adopted by TCEQ. These water bodies flow into the Navasota River below Lake Limestone but discharge below the impaired AUs addressed in this TMDL document.

E. coli data, collected at one monitoring station over the seven-year period of December 1, 2001 through November 30, 2008, were used in assessing attainment of the primary contact recreation use as reported in the 2010 Texas Integrated Report (TCEQ, 2011) for AU 1209_03. The 2010 assessment data indicate non-support of the primary contact recreation use because geometric mean concentrations exceed the geometric mean criterion at a measure of 138 MPN/100 mL. This AU impairment was carried forward from the 2010 assessment due to insufficient data collected. *E. coli* data, collected at one monitoring station over the seven-year period of December 1, 2005 through November 30, 2012, were used in assessing attainment of the primary contact recreation use as reported in the 2014 Texas Integrated Report (TCEQ, 2015). The 2014 assessment data indicate non-support of the primary contact recreation use for AU 1209_05 because geometric mean concentrations exceed the geometric mean criterion at a measure of 149 MPN/100 mL.

Point sources contributing *E. coli* to the impaired AUs include domestic wastewater and regulated stormwater. These sources are permitted to discharge into the watershed by the TCEQ. Three facilities have a permit to discharge domestic wastewater to the impaired AUs. Stormwater permits in the watershed of the impaired AUs include industrial facilities and construction activities.

Nonpoint source pollution also contributes *E. coli* to the river and its tributaries. These sources contribute diffusely across the watershed and are naturally occurring in some cases. Sources in this category include domestic animals, failing on-site sewage facilities (OSSFs), feral animals, agricultural activities, non-regulated stormwater runoff, and wildlife.

To evaluate *E. coli* loading in the watershed, a load duration curve (LDC) analysis was used. This enabled allowable pollutant loads and specific TMDL allocations for point and nonpoint sources of indicator bacteria to be quantified. The wasteload allocation (WLA) for wastewater treatment facilities (WWTFs) was established as the full permitted discharge flow rate multiplied by the instream geometric mean criterion. Future growth of domestic point sources was determined using population projections.

To develop the LDC and TMDL, paired *E. coli* samples and streamflow measurements were assessed. Available *E. coli* concentrations measured at TCEQ stations and paired streamflow records were obtained; however, the two did not always coincide. As a result, insufficient data were available to develop defensible LDCs for the impaired AUs. A Soil & Water Assessment Tool (SWAT) model was developed to predict streamflow at monitoring locations throughout the watershed. Modeled streamflow supplemented existing data and allowed LDC development.

The TMDL calculations in this report determine the assimilative capacity of each impaired AU under changing conditions, including future growth. WWTFs will be evaluated on a case-by-case basis. The endpoint for this TMDL is to maintain a geometric mean of *E. coli* concentrations below the 126 MPN/100 mL recreational standard.

Introduction

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

A TMDL is like a budget—it determines the amount of a particular pollutant that a water body can receive and still meet its applicable water quality standards. TMDLs are the best possible estimates of a water body's assimilative capacity for a pollutant under consideration. A TMDL is commonly expressed as a load with units of mass per period of time, but may be expressed in other ways.

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

These TMDLs address impairments to the primary contact recreation use due to elevated indicator bacteria geometric mean concentrations in the Navasota River below Lake Limestone watershed. These TMDLs take a watershed approach to address indicator bacteria impairments. While TMDL allocations were developed only for the impaired AUs of the Navasota River below Lake Limestone, 1209_03 and 1209_05, the entire project watershed (Figure 1) is described in the TMDL document.

Six tributary streams to the Navasota River below Lake Limestone that were impaired on the 2008 Texas Integrated Report were subject to a RUAA to determine the appropriate category of recreational use for each water body. In 2009, surveys and fieldwork began to document the current and past types and levels of use to gauge the appropriateness of the current water quality standard. Results indicated that primary contact recreation does not occur and that secondary contact recreation 1 is a more appropriate recreation use. The RUAA analysis resulted in a standards change recommendation for all six streams. The EPA approved secondary contract recreation use 1 category for Duck Creek

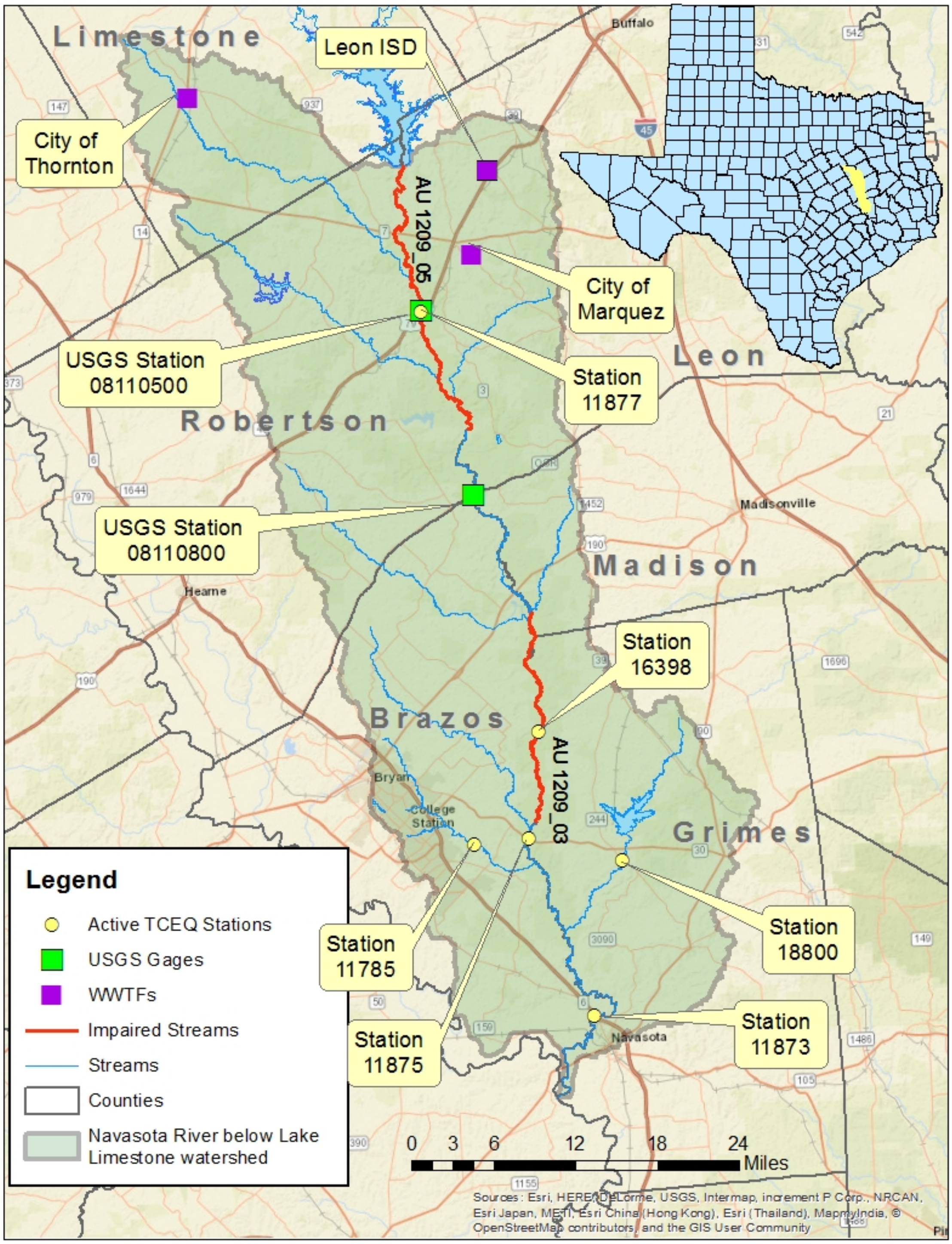


Figure 1. Navasota River below Lake Limestone watershed, including the impairments, municipal wastewater outfalls, USGS stream gages, and TCEQ monitoring stations

(1209H) and Shepherd Creek (1209J) in 2018. EPA action is pending for Wickson Creek (1209E), Cedar Creek (1209G), Gibbons Creek (1209I), and Steele Creek (1209K). As such, TMDLs for contact recreation use impairments on the 2014 Integrated Report for Wickson Creek, Duck Creek, Gibbons Creek, Shepherd Creek, and Steele Creek are not being developed. As of the 2014 Integrated Report Cedar Creek is no longer impaired. However, loads from Steele Creek, Duck Creek, Shepherd Creek, and Cedar Creek are included in the TMDLs for the Navasota River below Lake Limestone, as appropriate. Gibbons Creek and Wickson Creek are located below the impaired AUs, therefore they are not included in this TMDL.

Three other tributaries of the Navasota River below Lake Limestone also have elevated *E. coli* concentrations. In 2012, TMDLs for bacteria in Carters Creek (1209C), Burton Creek (1209L), and Country Club Branch (1209D) were adopted by the TCEQ and approved by the EPA. These water bodies flow into the Navasota River below Lake Limestone but discharge below the impaired AUs addressed in this TMDL document.

Section 303(d) of the Clean Water Act and the implementing regulations of the EPA in Title 40 of the Code of Federal Regulations (40 CFR), Part 130 describe the statutory and regulatory requirements for acceptable TMDLs. The EPA provides further direction in its *Guidance for Water Quality-Based Decisions: The TMDL Process* (EPA, 1991). This TMDL document has been prepared in accordance with those regulations and guidelines.

The TCEQ must consider certain elements in developing a TMDL. They are described in the following sections of this report:

- Problem Definition
- Endpoint Identification
- Source Analysis
- Linkage Analysis
- Margin of Safety
- Pollutant Load Allocation
- Seasonal Variation
- Public Participation
- Implementation and Reasonable Assurance

Upon adoption of the TMDL report by the TCEQ and subsequent EPA approval, these TMDLs will become an update to the state's Water Quality Management Plan (WQMP).

Problem Definition

The TCEQ first identified the impairments to the Navasota River below Lake Limestone in the *2002 Texas Integrated Report of Surface Water Quality for Clean Water Sections 305(b) and 303(d)* (Texas Integrated Report) and in each subsequent edition of the Texas Integrated Report. This document will establish TMDLs for impaired AUs 1209_03 and 1209_05 in the Navasota River below Lake Limestone watershed.

Watershed Overview

The Navasota River below Lake Limestone watershed is located in East-Central Texas and contains parts of six counties including Brazos, Grimes, Leon, Limestone, Madison, and Robertson. There are two reservoirs on the main stem of the Navasota River; thus, the watershed is 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). This segment of the Navasota River (1209) flows from the Sterling C. Robertson Dam, which forms Lake Limestone, downstream to its confluence with the Brazos River, south of State Highway 105 and west of the city of Navasota. The dam forms a major hydrological divide in the watershed and a logical breakpoint for assessment and evaluation purposes. The area of the watershed below Lake Limestone is 1,006,329 acres of mostly rural landscapes that consist of pastures, hay fields, and hardwood forests in bottomland and upland areas. Urbanization is not widespread but is primarily in the Bryan and College Station area in Brazos County. The river is a perennial freshwater stream, but the operations of Lake Limestone strongly influence its flow.

Segment and AU descriptions in the 2014 Integrated Report of the impaired portions of the watershed include:

- 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
    - 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

Ambient Indicator Bacteria Concentrations

The Navasota River below Lake Limestone and its tributaries must meet water quality standards to support primary contact recreation and maintain *E. coli* levels at or below a geometric mean of 126 MPN/100 mL. RUAAs were conducted on the Navasota River below Lake Limestone and six of its tributaries to document water body use, characteristics, and conditions in 2009. During this process, fishing and hunting were commonly observed in all AUs. Swimming and wading were also documented as occurring, but only in the Navasota River.

E. coli are a fecal indicator bacteria; however, *E. coli* themselves are not necessarily pathogenic, but may indicate the presence of other pathogenic organisms. If *E. coli* levels are found to exceed their water quality standards limits, the probability of contracting gastrointestinal illnesses is expected to increase.

In the case of AU 1209_03, limited data collection in the assessment period for the 2014 Integrated Report (December 1, 2005 through November 30, 2012) restricted the utility of the assessment. Only six samples were collected during this period (Table 1). Although the *E. coli* concentration geometric mean was 91.35 MPN/100 mL, the AU was still considered impaired, as it was in previous assessments, due to the lack of long-term evidence that it does meet water quality standards.

Water quality data from the dates represented in Table 1 were collected from the TCEQ Surface Water Quality Monitoring Information System on June 23, 2016, for the stations located on the impaired AUs and used in the development of these TMDLs. The period of historical data collection for TCEQ station 16398 was from September 2001 to February 2010 on AU 1209_03. The date range for TCEQ station 11877 was from January 2001 to February 2016 on AU 1209_05. Data for the stations vary due to intermittent monitoring activity.

Table 1. Navasota River AUs impaired due to elevated *E. coli*.

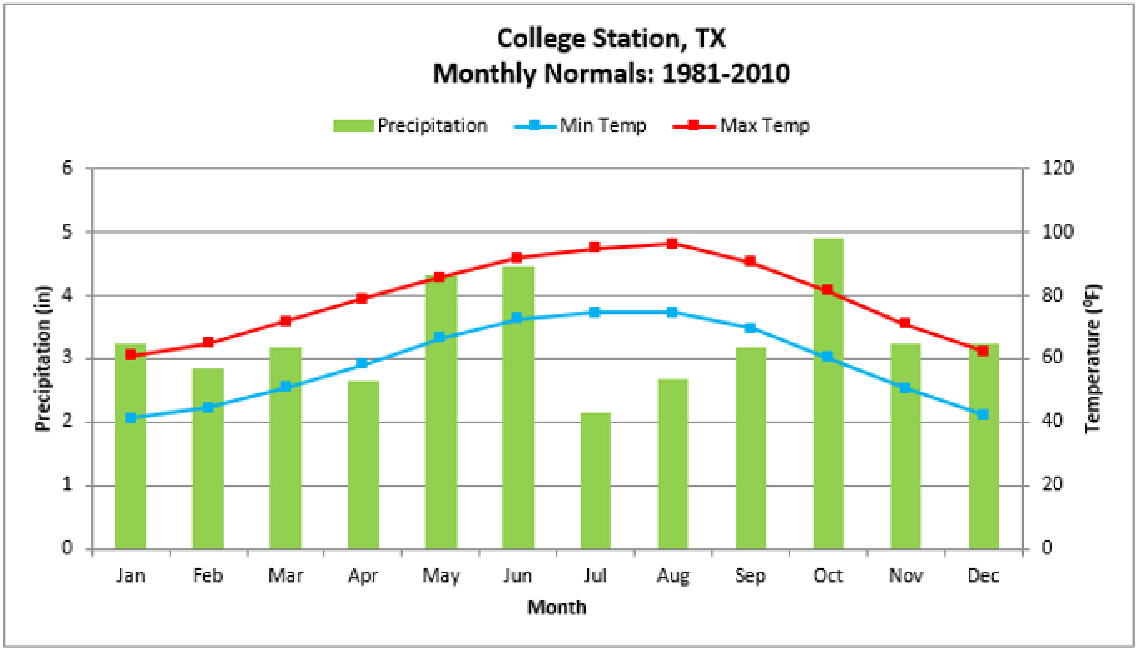
AU	Parameter	TCEQ Data Date Range	TCEQ Stations	TCEQ Total Samples	2014 Texas IR Total Samples [a]	2014 Texas IR Geometric Mean
1209_03	*E. coli*	September 2001 to February 2010	16398	57	6	91.35 [b]
1209_05	*E. coli*	January 2001 to February 2016	11877	91	27	148.59

[a] 2014 Integrated Report only assessed data collected between 12/1/2005 and 11/30/2012
[b] This AU impairment is carried forward from the 2010 assessment (26 samples; 137.7 geomean) due to the lack of data collected during the most recent assessment period indicating that it meets water quality standards.

Watershed Climate and Hydrology

The Navasota River below Lake Limestone 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 41˚F to 77˚F and average highs range from

62˚F to 96˚F (National Oceanic and Atmospheric Administration, 2014) (Figure 2). According to the Texas Water Development Board (TWDB) (Larkin and Bomar, 1983), the watershed generally receives 36 to 44 inches of rainfall annually (Figure 3).

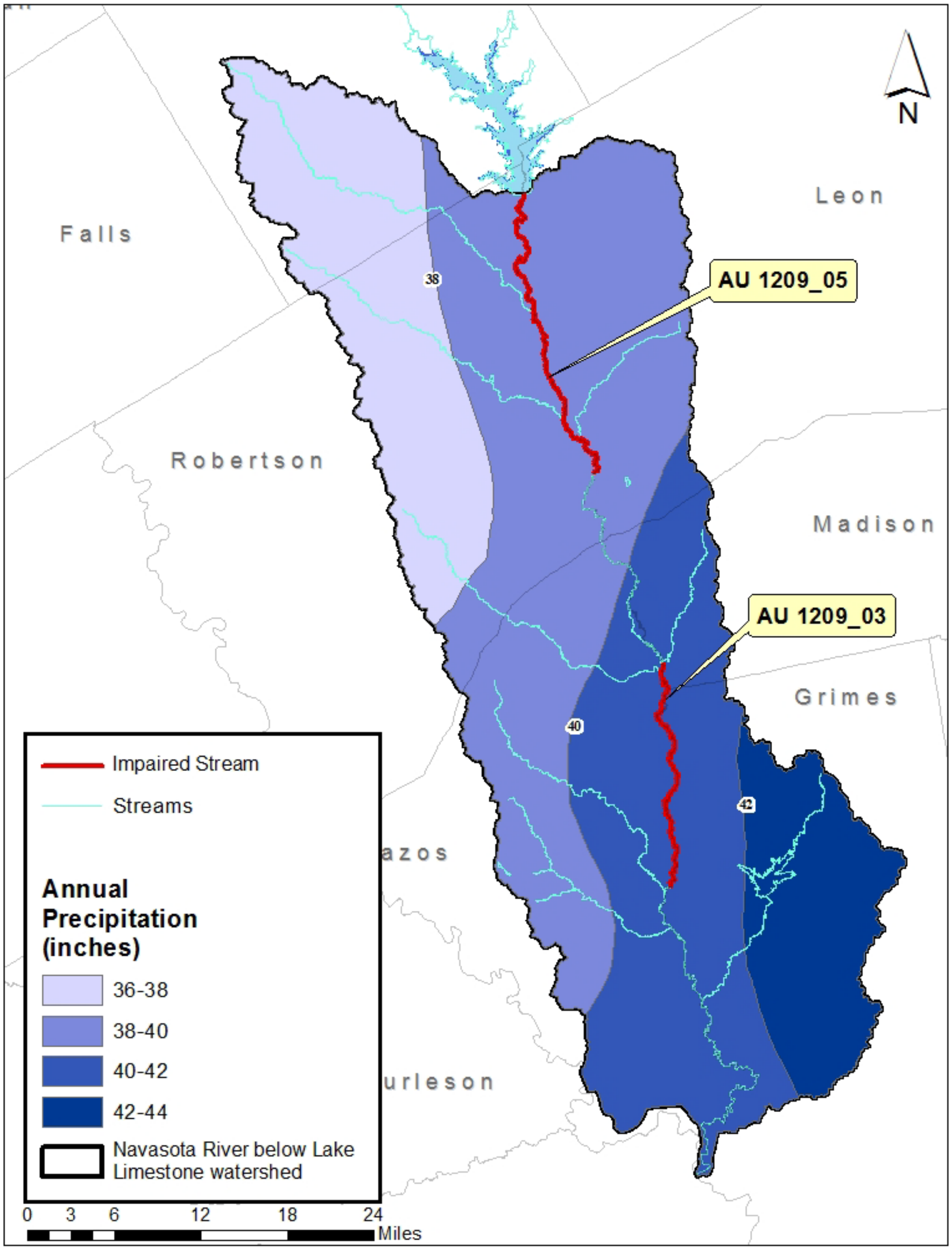


Source: National Oceanic and Atmospheric Administration, 2014

Figure 2. Average minimum and maximum air temperatures and total precipitation by month (1981-2010) College Station, TX

Watershed Population and Population Projections

Approximately 83 percent of the watershed population is estimated to reside in the Bryan and College Station area. Estimates from the 2010 United States Census Bureau (USCB) population census for the portion of each county in the watershed range from 1,419 in Madison County to 156,941 in Brazos County. Significant population growth is anticipated to occur over the next 50 years in the Navasota River below Lake Limestone watershed. According to estimates used in the 2017 State Water Plan (TWDB, 2014), populations are expected to increase 79.2 percent between 2020 and 2070 for the counties in the watershed (Table 2). The Navasota River below Lake Limestone watershed is predominantly rural, with most of the urban development centered around the cities of Bryan and College Station (Figure 4).



Source: Texas Water Development Board, 2014

Figure 3. Annual average precipitation (inches) for the Navasota River below Lake Limestone watershed

Table 2. Population, population density, and projections in the watershed

County	2010 County Population in Watershed	Population Density Per Square Mile	Projected Populations by Year (entire county)						Projected 50-year Increase (entire county)
			2020	2030	2040	2050	2060	2070	
Brazos	156,941	376.5	227,654	264,665	302,997	349,894	400,135	455,529	100.1 %
Grimes	11,170	34.5	29,441	32,179	34,258	36,454	38,277	39,867	35.4 %
Madison	1,419	20.2	14,753	15,817	16,786	17,872	18,886	19,877	34.7 %
Leon	5,235	21.3	18,211	19,536	20,603	22,071	23,340	24,582	35.0 %
Limestone	1,735	11.5	25,136	26,615	27,817	29,134	30,206	31,152	23.9 %
Robertson	4,540	12.4	18,358	20,150	21,801	23,525	25,174	26,771	45.8 %
Totals	181,040	n/a	333,553	378,962	424,262	478,950	536,018	597,778	79.2 %

Source: Texas Water Development Board, 2014

Land Use

Land use/land cover for the watershed is divided according to the National Land Cover Database (NLCD) map classifications. Most land in the Navasota River below Lake Limestone watershed is pasture/hay land (37.9 percent) and forest (24.8 percent) (Table 3). There is limited cultivated crop production. Crop data from the U.S. 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 in the watershed is within the cities of Bryan and College Station in the southwestern portion of the watershed.

The land use/land cover data for the Navasota River below Lake Limestone watershed were obtained from the U.S. Geological Survey (USGS) 2011 NLCD (Figure 5) and are represented by the following categories and definitions (USGS, 2014).

Open Water - areas of open water, generally with less than 25 percent cover of vegetation or soil.

Developed, Open Space - areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.

Developed, Low Intensity - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20 percent to 49 percent of total cover. These areas most commonly include single-family housing units.

Developed, Medium Intensity - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50 percent to 79 percent of the total cover. These areas most commonly include single-family housing units.

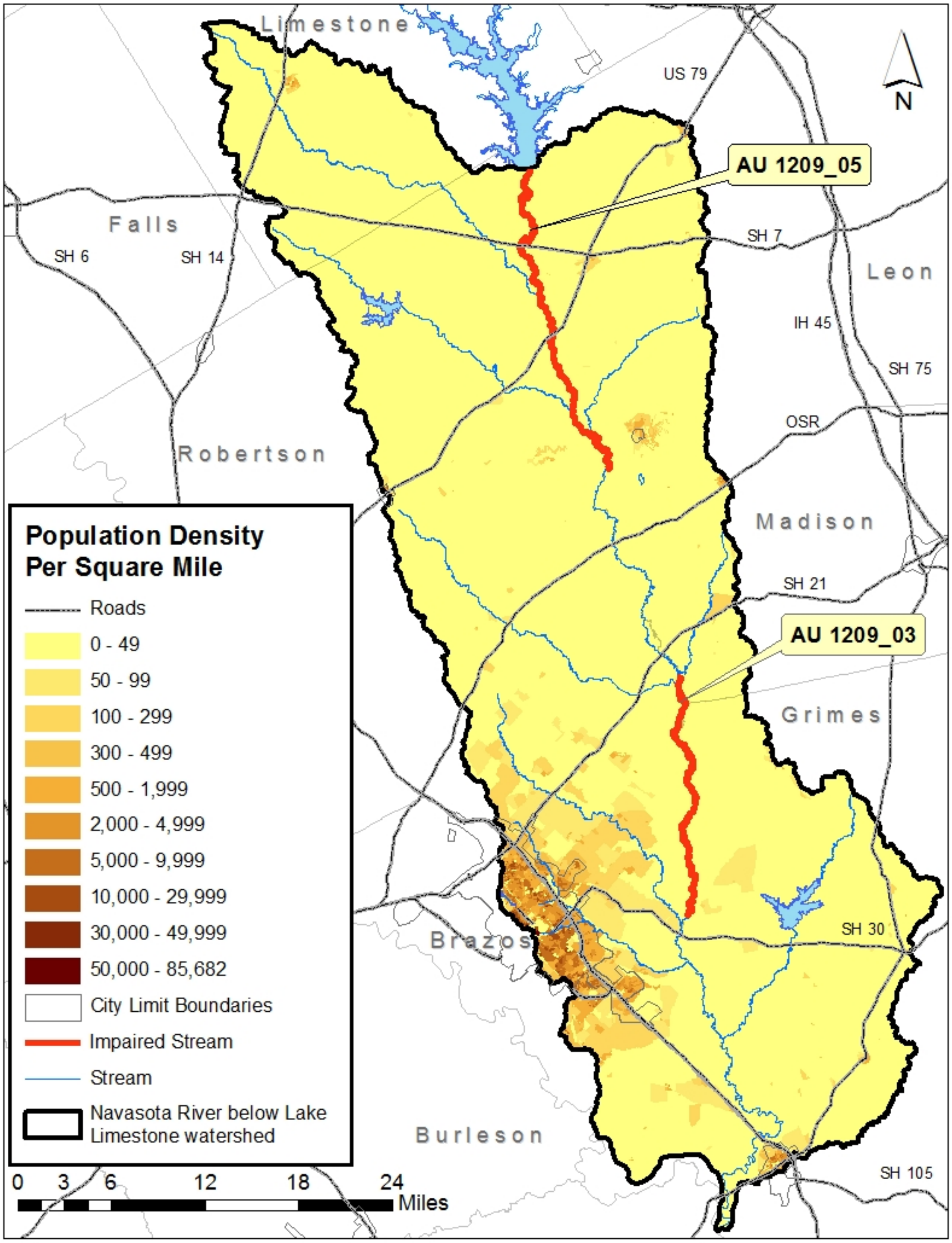


Figure 4. Population density per square mile in the Navasota River below Lake Limestone watershed

Table 3. Land use/land cover in the Navasota River below Lake Limestone watershed

2011 NLCD Classification	Acres	% Total
Open Water	10,987	1.1
Developed (Open Space; Low, Medium, and High Intensity)	77,367	7.7
Barren Land (Rock/Sand/Clay)	9,517	0.9
Forest (Deciduous, Evergreen, and Mixed)	249,547	24.8
Shrub/Scrub	93,072	9.2
Grassland/Herbaceous	81,117	8.1
Pasture/Hay	381,727	37.9
Cultivated Crops	19,222	1.9
Wetlands (Woody and Emergent Herbaceous)	83,773	8.4
Total	**1,006,329**	**100%**

Developed High Intensity - highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses, and commercial/industrial areas. Impervious surfaces account for 80 percent to 100 percent 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 percent of total cover.

Deciduous Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.

Evergreen Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.

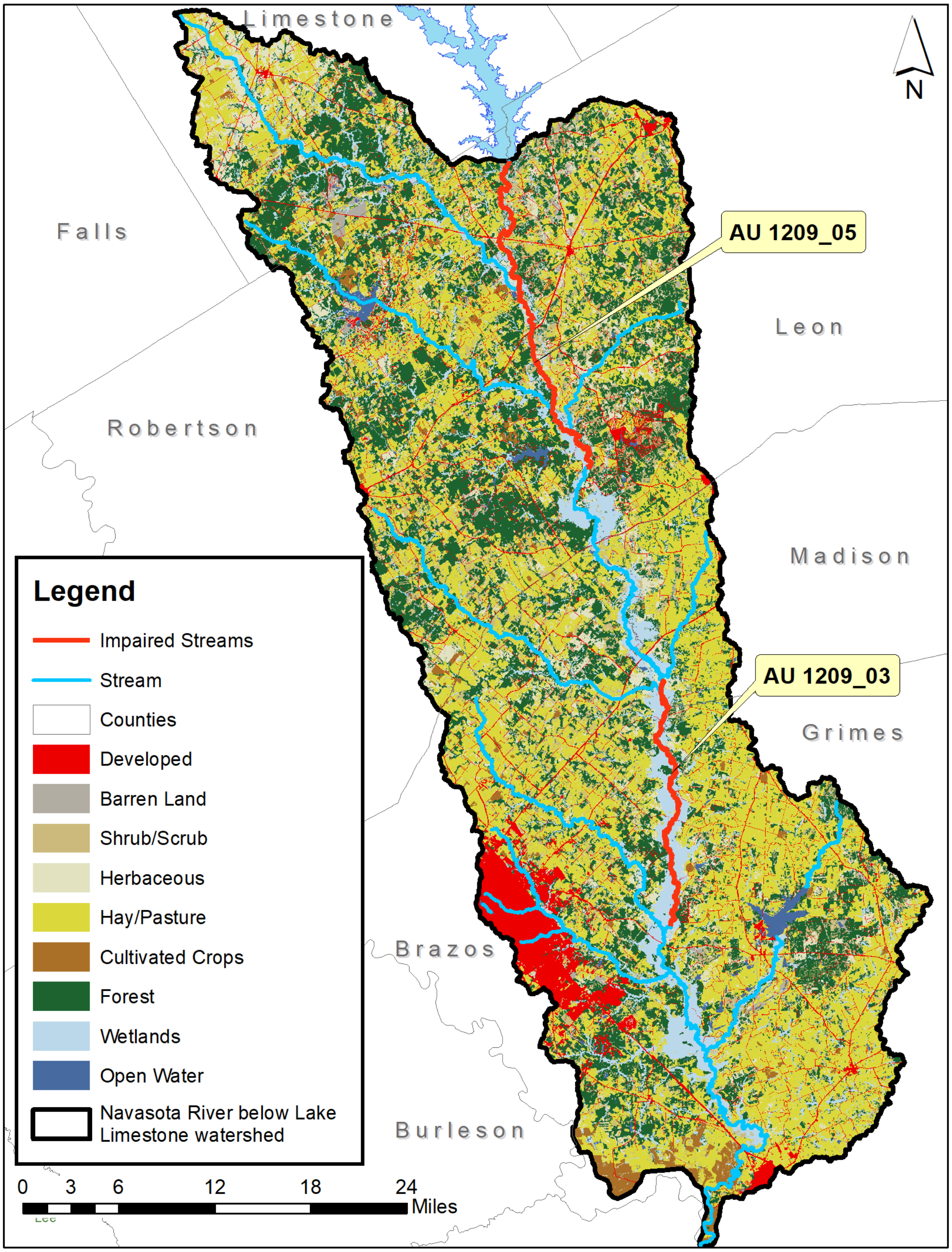


Figure 5. 2011 NLCD land use/land cover within the Navasota River below Lake Limestone watershed

Mixed Forest - areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent of total tree cover.

Shrub/Scrub - areas dominated by shrubs less than 5 meters tall, with shrub canopy typically greater than 20 percent of total vegetation. This class includes true shrubs, young trees in an early successional stage, or trees stunted from environmental conditions.

Grassland/Herbaceous - areas dominated by graminoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.

Pasture/Hay - areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.

Cultivated Crops - areas used 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 percent 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 percent of vegetative cover, and the soil or substrate is periodically saturated with or covered with water.

Emergent Herbaceous Wetlands - areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover, and the soil or substrate are periodically saturated with or covered with water.

Soils

According to data retrieved from the USDA Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (NRCS, 2013), soils categorized in all four Hydrologic Soil Groups can be found in the watershed (Figure 6). Soils in Group A cover approximately 17 percent of the watershed and are typically sands and loamy sands with a relatively high infiltration rate when wetted. Soils in Group B are typically silt loams or loams with a moderate infiltration rate when thoroughly wet. Soils in this group cover approximately 14 percent 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 16 percent 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 53 percent of the watershed is made up of soils in this group.

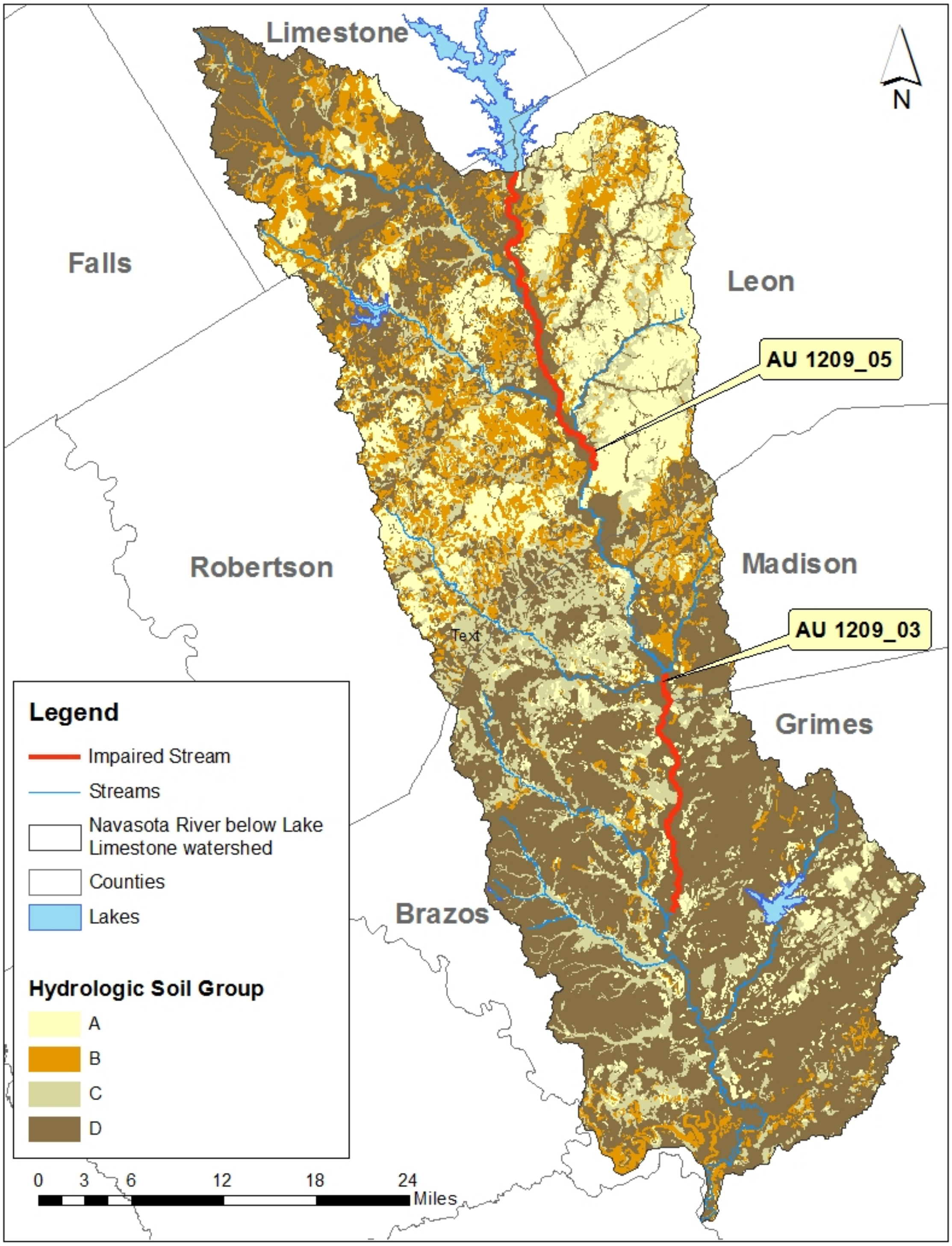


Figure 6. Hydrologic Soil Groups for the Navasota River below Lake Limestone

Endpoint Identification

All TMDLs must identify a quantifiable water quality target that indicates the desired water quality condition and provides a measurable goal for the TMDL. The TMDL endpoint also serves to focus the technical work to be accomplished and as a criterion against which to evaluate future conditions.

The endpoint for the TMDLs in this report is to maintain concentrations of *E. coli* below the geometric mean criterion of 126 MPN/100 mL. This endpoint is identical to the geometric mean criterion in the 2010 Texas Surface Water Quality Standards (TCEQ, 2010) for primary contact recreation in freshwater.

Source Analysis

Pollutants may come from several sources, both regulated and unregulated. Regulated pollutants, referred to as “point sources,” come from a single definable point, such as a pipe, and are regulated by permit under the Texas Pollutant Discharge Elimination System (TPDES) or the National Pollutant Discharge Elimination System (NPDES). WWTFs and stormwater discharges from industries, construction, and municipal separate storm sewer systems (MS4s) are considered point sources of pollution.

Unregulated sources are typically nonpoint in origin, meaning the pollutants originate from multiple locations and can be carried primarily by rainfall runoff into surface waters. Nonpoint sources are not regulated by permit.

With the exception of domestic WWTFs, which receive individual WLAs (see the “Wasteload Allocation” section), the regulated and unregulated sources in this section are presented to give a general account of the different sources of bacteria identified in the watershed. These are not meant to be used for allocating bacteria loads or interpreted as precise inventories and loadings.

Regulated Sources

Regulated sources are controlled by permit under the TPDES and NPDES programs. The regulated sources in the TMDL watershed include domestic WWTF outfalls and stormwater discharges from industries and construction.

Domestic and Industrial Wastewater

Domestic WWTFs treat wastewater and generally discharge limited amounts of *E. coli*. While there are 13 individual domestic WWTFs in the Navasota River below Lake Limestone watershed, only three WWTFs, for the entities of City of Marquez, Leon ISD, and City of Thornton, have *E. coli* limits in their permits and discharge to one of the impaired AUs.

Table 4 lists the individually permitted discharge facilities in the Navasota River below Lake Limestone watershed. As of February 2017, there were 22 TPDES/NPDES permits for facilities in the watershed. These include wastewater permits, cooling water discharge permits, industrial discharges, and mine dewatering discharge permits.

There are nine individual industrial WWTFs in the watershed of the Navasota River below Lake Limestone, five of which discharge to the impaired AUs. Effluents from industrial WWTFs vary and may include a combination of treated wastewater, stormwater, and treated domestic wastewater. The effluent from the five industrial WWTFs discharging to the impaired AUs do not include treated domestic wastewater and are therefore not included in the TMDL allocations for regulated wastewater. Of these, two facilities (Oak Grove Management Co, LLC – WQ0001986000 and Luminant Mining Co, LLC – WQ0002699000) are authorized to discharge stormwater. These facilities will be included in the TMDL allocations for regulated stormwater.

General Wastewater Permits

Discharges of processed wastewater from certain types of facilities are required to be covered by one of several TPDES general permits:

- TXG110000 – concrete production facilities
- TXG130000 – aquaculture production facilities
- TXG340000 – petroleum bulk stations and terminals
- TXG500000 – quarries in John Graves Scenic Riverway
- TXG670000 – hydrostatic test water discharges
- TXG830000 – water contaminated by petroleum fuel or petroleum substances
- TXG920000 – concentrated animal feeding operations
- WQG100000 – wastewater evaporation
- WQG20000 – livestock manure compost operations (irrigation only)

A review of general wastewater permits was conducted to understand the regulated activities occurring in the Navasota River below Lake Limestone. Many general wastewater permits do not authorize discharges and those that do are not expected to contain domestic wastewater. One concentrated animal feeding operation (CAFO) was found (TXG920363) in the watershed of the impaired AUs. CAFOs do not discharge to water bodies when operating, according to their permits, but may do so if a system failure occurs.

Sanitary Sewer Overflows

Sanitary sewer overflows (SSOs) are unauthorized discharges that must be addressed by the responsible party, either the TPDES permittee or the owner of the collection system that is connected to a permitted system. SSOs in dry weather most often result from blockages in the sewer collection pipes caused by tree roots, grease, and other debris. Inflow and infiltration (I&I) are typical causes of SSOs under high flow conditions 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. Data presented in the Consolidated Compliance and Enforcement Data Systems database, maintained by the TCEQ's Office of Compliance and Enforcement, may not represent all SSOs nor do permitted entities always know when a SSO occurs. As of January 1, 2016, 54 SSOs were reported in the watershed totaling 158,895 gallons. However, none of these incidences occurred in the impaired AUs (Table 5).

Table 4. Permitted discharge facilities in the Navasota River below Lake Limestone watershed

TPDES Permit Number	NPDES Permit Number	Facility Name (effluent type) [a]	Final Receiving Navasota River (1209) AU	Final Permitted Discharges (MGD) [b]	Recent Discharge (MGD) [c]
WQ0013980001	TX0117579	City of Marquez WWTF (WW)	1209_05	0.040	0.020[d]
WQ0010824001	TX0075639	City of Thornton WWTF (WW)	1209_05	0.041	0.016
WQ0014659002	TX0135127	Leon ISD WWTF (WW)	1209_05	0.020	*
WQ0004770000	TX0124401	Linde Gas North America, LLC Jewett Plant (IW)	1209_05	0.040	0.011
WQ0001986000	TX0068021	Oak Grove Management Co, LLC Oak Grove Steam Electric Station (CW/IW/SW)	1209_05	1610	1542
WQ0002699000	TX0076465	Luminant Mining Co, LLC Oak Grove Lignite Mining Area (IW/SW)	1209_05	Intermittent and Flow-variable	2
WQ0005138000	TX0135615	Sanderson Farms, Inc Franklin Feed Mill (IW)	1209_05	0.040	0.014
WQ0001176000	TX0001368	U.S. Silica Co Kosse Plant (IW)	1209_05	2.500	1.600
WQ0013931001	TX0116378	City of Anderson WWTF (WW)	1209_01	0.065	0.008[e]
WQ0010231001	TX0071790	City of Navasota WWTF (WW)	1209_01	1.800	0.637
WQ0014879001	TX0131440	Ni America Texas Development, LLC Myers Reserve WWTF (WW)	1209_01	0.075	*
WQ0010426001	TX0022616	City of Bryan Burton Creek WWTF (WW)	1209_02	8.000	4.590
WQ0013153001	TX0098663	City of College Station Carter Lake WWTF (WW)	1209_02	0.009	0.006

TPDES Permit Number	NPDES Permit Number	Facility Name (effluent type)[a]	Final Receiving Navasota River (1209) AU	Final Permitted Discharges (MGD)[b]	Recent Discharge (MGD)[c]
WQ0010024003	TX0093262	City of College Station Lick Creek WWTF (WW)	1209_02	2.000	1.178
WQ0010024006	TX0047163	City of College Station Carters Creek WWTF (WW)	1209_02	9.500	6.330
WQ0012296001	TX0085456	ILP College Station, LLC Glen Oaks Mobile Home Park WWTF (WW)	1209_02	0.013	0.001
WQ0015556001	TX0137570	Smiling Mallard Development, Ltd. Lakes & South College Station Development WWTF (WW)	1209_02	0.250	*
WQ0003996000	TX0120146	Tenaska Frontier Partners, Ltd Tenaska Frontier Generating Station (IW/SW)	1209_02	2.500	0.764
WQ0004002000	TX0002747	Texas A&M University Central Utilities Plant (IW/SW)	1209_02	0.930	0.580
WQ0002120000	TX0074438	Texas Municipal Power Agency Gibbons Creek Steam Electric Station (IW/SW/WW)	1209_02	Intermittent and flow-variable	1.140
WQ0002460000	TX0083101	Texas Municipal Power Agency Gibbons Creek Lignite Mine (SW)	1209_02	Intermittent and flow-variable	3.888
WQ0001906000	TX0027952	City of Bryan Atkins Street Power Plant (IW/SW)	1209_02	0.385	0.073

[a] CW (cooling water), IW (industrial wastewater), SW (stormwater), WW (domestic wastewater)

[b] MGD = million gallons per day

[c] Based on average discharge from July 7, 2013 to June 30, 2016

[d] Based on average discharge from January 2015 to January 2017

[e] Based on average discharge from November 2011 to December 2016

* No data to report

Table 5. Summary of SSO incidences

AU	Number of SSOs	Total Volume (gallons)	Median SSO Volume (gallons)	Median SSO Duration (hours)
1209_01	6	150,800	5,200	2.5
1209_02	48	8,095	50	2
1209_03	None reported	-	-	-
1209_04	None reported	-	-	-
1209_05	None reported	-	-	-

TPDES-Regulated Stormwater

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

1) Stormwater subject to regulation, which is any stormwater originating from TPDES/NPDES regulated MS4s, industrial facilities, and regulated construction activities.

2) Stormwater runoff not subject to regulation.

The TPDES/NPDES MS4 Phase I and II rules require municipalities and certain other entities in urban areas to obtain permit coverage for their stormwater systems. A regulated MS4 is a publicly owned system of conveyances and includes ditches, curbs, gutters, and storm sewers that do not connect to a wastewater collection system or treatment facility. Phase I permits are individual permits for large and medium-sized communities with populations of 100,000 or more based on the 1990 USCB population census, whereas the Phase II general permit regulates smaller communities within a USCB defined urbanized area. The purpose of an MS4 permit is to reduce discharges of pollutants in stormwater to the “maximum extent practicable” by developing and implementing a Stormwater Management Program (SWMP). The SWMP describes the stormwater control practices that will be implemented consistent with permit requirements to minimize the discharge of pollutants from the MS4. The permits require that the SWMPs specify the best management practices (BMPs) to meet several minimum control measures (MCMs) that, when implemented in concert, are expected to result in significant reductions of pollutants discharged into receiving water bodies. Phase II MS4 MCMs include:

- Public education, outreach, and involvement;
- Illicit discharge detection and elimination;
- Construction site stormwater runoff control;
- Post-construction stormwater management in new development and redevelopment;
- Pollution prevention and good housekeeping for municipal operations; and
- Industrial stormwater sources.

Phase I MS4 individual permits have similar MCMs organized a little differently and are further required to perform water quality monitoring.

The geographic region of the Navasota River below Lake Limestone watershed covered by Phase I and II MS4 permits is that portion of the area within the jurisdictional boundaries of the regulated entity. For Phase I individual permits, the jurisdictional area is defined by the city limits. For Phase II general permit authorizations, the jurisdictional area is defined as the intersection or overlapping areas of the MS4 boundaries and the 2000 or 2010 U.S. Census of urbanized areas. The portion of the Navasota River below Lake Limestone watershed for the impaired AUs does not include any areas with Phase I or Phase II MS4 permits.

In the absence of areas regulated by Phase I and Phase II MS4 areas, a review of other stormwater permits is conducted. The area of the watershed with regulated stormwater is estimated by determining coverage by individual industrial stormwater WWTFs, multi-sector, and construction permits. As of April 30, 2018, 270 stormwater authorizations were issued under a general permit, with 234 of these facilities located in Brazos County. The remaining facilities with stormwater permit authorizations are located in Grimes (17), Limestone (5), Leon (7), and Robertson (7) counties. Brazos County stormwater permit authorizations include authorizations for construction activities, industrial activities, and Phase II MS4s. In addition to the general stormwater authorizations, there are two individual industrial WWTFs (Oak Grove Management Co, LLC – WQ0001986000 and Luminant Mining Co, LLC – WQ0002699000) that are authorized to discharge stormwater.

Municipal Separate Storm Sewer Systems

There are three Phase II and one Phase I MS4 permit authorizations in the watershed, which account for the bulk of permitted stormwater in the watershed; however, these are downstream of the impaired AUs, and are not included in the TMDL calculations (Table 6).

Table 6. MS4 permits associated with the Navasota River below Lake Limestone watershed

Regulated Entity Name	NPDES Permit Number
Brazos County	TXR040172
City of Bryan	TXR040336
City of College Station	TXR040008
Texas Department of Transportation	TXS002101

Illicit Discharges

Pollutant loads can enter streams from MS4 outfalls that carry authorized sources as well as illicit discharges under both dry- and wet-weather conditions. The term "illicit discharge" is defined in TPDES Small (Phase II) MS4 General Permit TXR040000 as "Any discharge to a municipal separate storm sewer that is not entirely composed of stormwater, except discharges pursuant to this general permit or a separate authorization and discharges resulting from emergency firefighting activities." Illicit discharges can be categorized as either direct or indirect contributions. Examples of illicit discharges identified in the *Illicit Discharge Detection and Elimination Manual: A Handbook for Municipalities* (NEIWPCC, 2003) include:

Direct Illicit Discharges:

- sanitary wastewater piping that is directly connected from a home to the storm sewer,
- materials that have been dumped illegally into a storm drain catch basin,
- a shop floor drain that is connected to the storm sewer, and
- a cross-connection between the sanitary sewer and storm sewer systems.

Indirect Illicit Discharges:

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

Unregulated Sources

Unregulated sources of bacteria are generally nonpoint. Nonpoint source loading can enter streams through distributed, nonspecific locations, which may include urban runoff not covered by a permit, wildlife, various agricultural activities, agricultural animals, land application fields, failing OSSFs, unmanaged and feral animals, and domestic pets.

Unregulated Agricultural Activities and Domesticated Animals

A number of agricultural activities that do not require permits can be potential sources of fecal indicator bacteria loading. Livestock are present throughout rural portions of the project watershed.

Table 7 provides estimated numbers of selected livestock in the watershed based on the 2012 Census of Agriculture conducted by the USDA (USDA National Agricultural Statistics Service, 2014b). The county-level estimated livestock populations were distributed based on geographic information system (GIS) calculations of Pasture/Hay land use/land cover in the watershed, per the 2011 NLCD (USGS, 2014). Local stakeholders, including local soil and water conservation district board members, and Texas State Soil and Water Conservation Board (TSSWCB) staff reviewed livestock population estimates. These livestock numbers, however, were not used to develop an allocation of allowable bacteria loading to livestock.

Table 7. Grazing livestock populations in the Navasota River below Lake Limestone watershed

County	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**	**3,124**	**1,142**

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

Commercial poultry operations, not tracked in the Census of Agriculture, also exist in the watershed. According to the TSSWCB, as of 2015 there were 57 poultry facilities in the watershed that house almost 9.9 million birds. Poultry facilities are required to obtain a WQMP before operations begin. WQMPs prescribe proper handling and utilization of produced litter to ensure adequate water quality protection. As a result, this potential source of *E. coli* in the watershed is not considered significant.

Wildlife and Unmanaged Animals

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

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. Texas Parks and Wildlife Department (TPWD) survey data from the watershed was used for deer estimates and stakeholder feedback was used for feral hog estimates.

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

The deer population density is estimated from annual survey data from TPWD at 32 ac/deer of land suitable for the deer (pasture/hay, grassland/herbaceous, shrub/scrub, cropland, forests, and wetlands). This yields an estimate of 28,392 deer.

Numerous other wildlife species reside in the Navasota River below Lake Limestone 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 the wildlife 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.

Dogs and other urban animals can also contribute fecal bacteria to water bodies. The American Veterinary Medical Association (AVMA) estimates 0.584 dogs per household. Using 2010 USCB 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 8).

Table 8. Estimates of dog populations in the Navasota River below Lake Limestone watershed

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**

Source: AVMA, 2012; USCB, 2010

On-Site Sewage Facilities

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

Several pathways of the liquid waste in OSSFs afford opportunities for bacteria to enter ground and surface waters, if the systems are not properly operating. However, if properly designed and operated, OSSFs would be expected to contribute virtually no fecal bacteria to surface waters. For example, it has been reported that less than 0.01 percent of fecal coliforms originating in household waste move further than 6.5 feet down gradient of the drainfield of a septic system (Weikel et al., 1996). Reed, Stowe, and Yanke LLC (2001) provide information on estimated failure rates of OSSFs for different regions of Texas. Estimates for the Navasota River below Lake Limestone watershed were derived by discussing failures with County Designated Representatives, providing an estimated failure rate of about 10.2 percent.

The number of OSSFs expected in the watershed was derived by applying a multifaceted estimation approach that uses 2010 USCB 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 Navasota River below Lake Limestone watershed; however, this number is increasing. Of these, 1,749 OSSFs may be failing based on the estimated 10.2 percent failure rate. Table 9 shows the

OSSFs for each impaired AU. Other OSSFs in the watershed are located downstream of the impaired AUs and thus are not contributing to bacteria concentrations.

Table 9. OSSF estimates for the impaired AUs

AU	Estimated OSSFs
1209_03	10,997
1209_05	3,730

Source: Census Bureau, 2010; Gregory et al., 2013

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 and enteric bacteria reproduction in the environment cannot be fully understood. However, neither reproduction nor die-off rates of indicator bacteria were considered in the bacteria source loading estimates for the TMDL watershed.

Linkage Analysis

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

Generally, direct fecal deposition can be identified when there are high bacteria concentrations at 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 regulated and unregulated 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 LDCs assumes a one-to-one 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 (LA). Pollutant load allocations are based on the distribution of loadings assigned to WWTFs, a fractional proportioning of remaining loads based on the area of the watershed under stormwater regulation, and assigning the remaining portion to unregulated stormwater.

To develop streamflow records, a SWAT model was constructed for the Navasota River below Lake Limestone watershed. Lake Limestone's release was incorporated into the model as an inlet, while the outlet is located at the river's confluence with the Brazos River. The development of the streamflow records using SWAT is discussed further in Appendix A. Additional details are provided in the *Technical Support Document for Total Maximum Daily Loads for Indicator Bacteria in the Navasota River Watershed*.

Streamflow simulation calibration, validation, sensitivity analysis, and uncertainty were 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 downstream-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-Sutcliffe coefficient (NSE) of greater than 0.50, in accordance with the project Quality Assurance Project Plan.

Load Duration Curve Analysis

LDCs are graphs of the frequency distribution of loads of pollutants in a stream. In the case of these TMDLs, the loads shown are of *E. coli* bacteria in MPN/day. LDCs are derived from flow duration curves (FDCs). A detailed discussion of FDCs and LDCs is included in Appendix A of this document. The LDCs shown in the following figures represent the maximum acceptable load in the stream that will result in achievement of the TMDL water quality target. The basic steps to generate LDCs involve:

- Preparing FDCs using SWAT to generate flow records that have incorporated the full permitted flow from WWTFs at the monitoring stations chosen for analysis (see Appendix A for further discussion of SWAT model application);
- Identifying the critical flow range from the FDCs to define the TMDL. The high flow regime (0-10th percentile range) was chosen as most protective of the contact recreation use in the Navasota River below Lake Limestone even though swimming is not expected to occur at high flows due to safety concerns, nor at very low flows due to a lack of sufficient depth;
- Converting the FDCs to LDCs;

- Estimating existing indicator bacteria loading in the receiving water using ambient water quality data collected at the stations selected for analysis; and
- Interpreting LDCs to understand the relative contributions of regulated and unregulated sources.

Bacteria LDCs were developed by multiplying each streamflow value along the FDCs by the *E. coli* geometric mean criterion (126 MPN/100 mL) and by the conversion factor to convert to loading in MPN per day. This effectively displays the LDC as the TMDL curve of maximum allowable loading:

TMDL (MPN/day) = Criterion * flow [cubic feet per second (cfs)] * conversion factor

Where:

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

Conversion factor (to MPN/day) = 28,316.846 mL/ft^3 * 86,400 seconds/day (s/d)

Exceedance values along the x-axis represent the percent of days that flow was at or above each bacteria load value on the y-axis. Exceedance values near 100 percent occur during low flow or drought conditions while values approaching zero percent 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.

The LDC can be refined by dividing the curve into flow-regime regions to analyze exceedance patterns in smaller portions of the duration curves. This approach can assist in determining streamflow conditions under which exceedances are occurring. A commonly used set of regimes that is provided in Cleland (2003) is based on the following five intervals along the x-axis of the FDCs and LDCs: (1) 0-10 percent (high flows); (2) 10-40 percent (moist conditions); (3) 40-60 percent (mid-range flows); (4) 60-90 percent (dry conditions); and (5) 90-100 percent (low flows). Additional information explaining the LDC method may be found in Cleland (2003) and Nevada Division of Environmental Protection (2003).

The median loading of the high flow regime (0-10 percent exceedance) is used for the TMDL calculations. The median loading of the high flow regime is represented by the five percent exceedance and is used for the TMDL calculations because it represents a reasonable yet high value for the allowable pollutant load allocation.

Two LDCs were developed for stations 16398 and 11877 from historical bacteria data obtained from the TCEQ Surface Water Quality Monitoring Information System database, and they were superimposed on the allowable bacteria LDC.

Load Duration Curve Results

To develop the TMDL allocation, LDCs were constructed for two monitoring stations within the Navasota River below Lake Limestone watershed (Figure 7 and Figure 8). LDCs for each impaired AU demonstrate the allowable load under the geometric mean criterion (126 MPN/100mL) and the single sample criterion (399 MPN/100mL) 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.

Based on these LDCs (Figure 7 and Figure 8) and the addition of historical *E. coli* data, the following broad linkage statements can be made. For the Navasota River below Lake Limestone watershed, the *E. coli* data indicate that elevated bacteria loadings occur under all flow conditions, but are most elevated under the highest flows. Regulated stormwater is considered only a minor contributor, as it comprises a very small portion of the watershed (1.33 percent). Unregulated stormwater and instream resuspension of *E. coli* likely comprise the majority of high flow-related loadings. Elevated *E. coli* loadings under lower flow conditions cannot be reasonably attributed exclusively to WWTFs due to outfalls being located a considerable distance from Stations 16398 and 11877.

Thus, other sources of bacteria loadings under lower flows and in the absence of overland flow contributions (i.e., without stormwater contribution) are most likely contributing bacteria directly to the water, as could occur through direct deposition of fecal material from wildlife, feral hogs, and livestock. Actual contributions of bacteria loadings from direct deposition cannot be determined using LDCs.

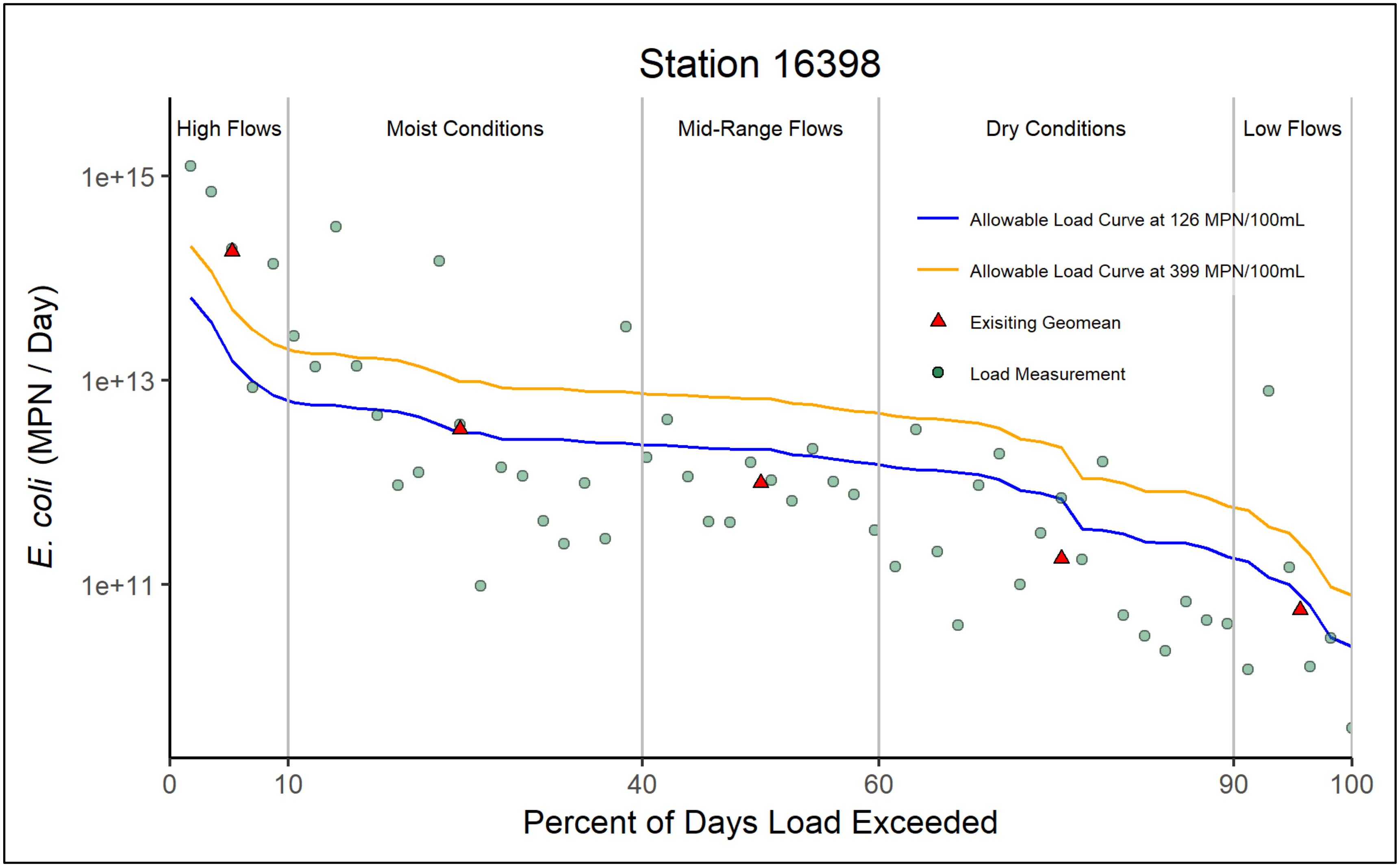


Figure 7. Load duration curve at Station 16398 Navasota River at Grimes (AU 1209_03) for the period of September 2001 through February 2010

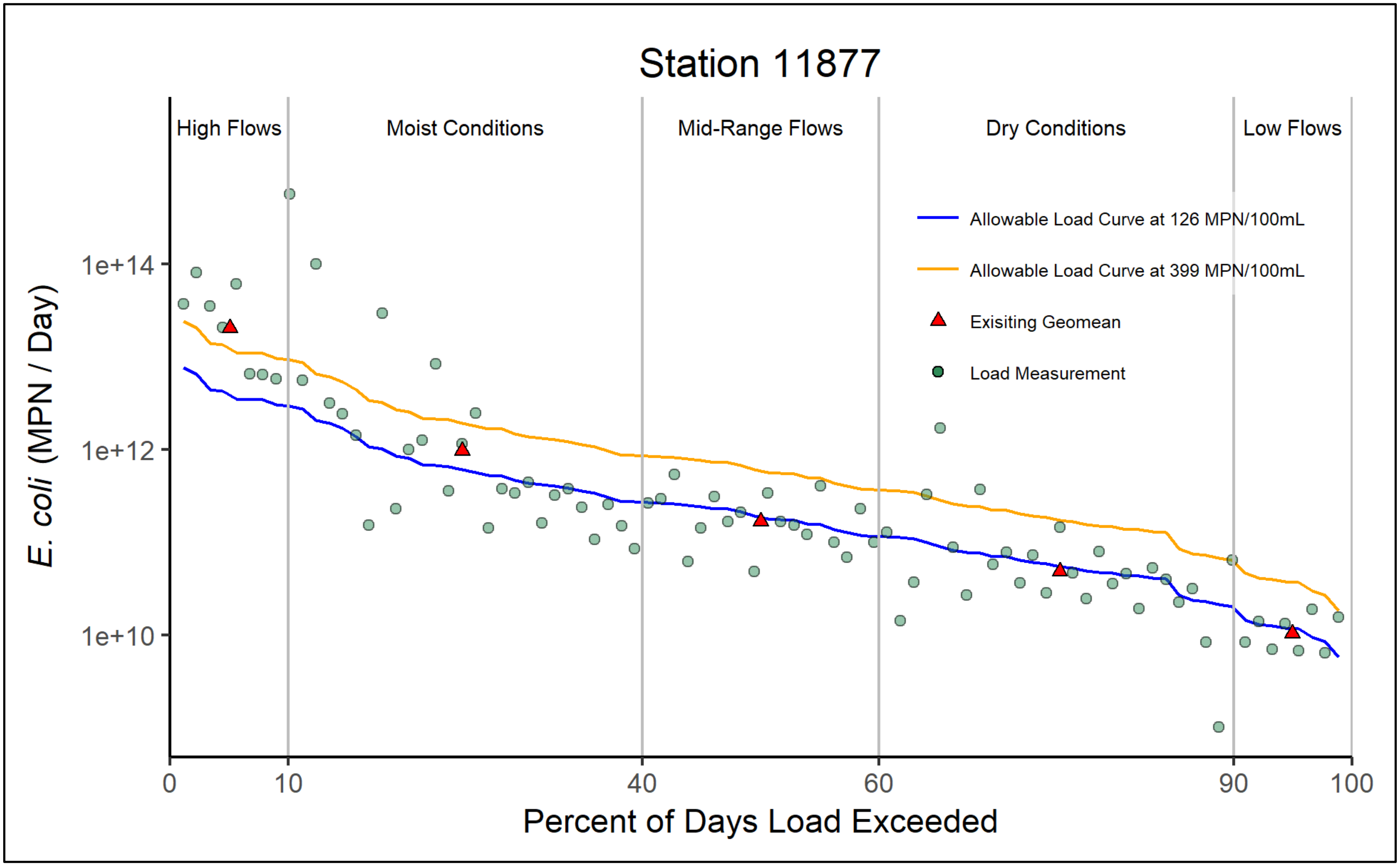


Figure 8. Load duration curve at Station 11877 Navasota River at U.S. 79 (AU 1209_05) for the period of January 2001 through February 2016

Margin of Safety

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

1) Implicitly incorporating the MOS using conservative model assumptions to develop allocations; or
2) Explicitly specifying a portion of the TMDL as the MOS and using the remainder for allocations.

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

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

Pollutant Load Allocation

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

$$TMDL = WLA + LA + FG + MOS$$

Where:

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

LA = load allocation, the amount of pollutant allowed by unregulated sources

FG = loadings associated with future growth from potential regulated facilities

MOS = margin of safety

As stated in 40 CFR §130.2(1), TMDLs can be expressed in terms of mass per time, toxicity, or other appropriate measures.

These TMDLs use the median value within the high flow regime (five percent exceedance) for both impaired AUs in the Navasota River below Lake Limestone watershed.

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 five percent exceedance (the median value of the high flow regime) and is the TMDL. Values of allowable loadings within the Navasota River below Lake Limestone watershed are shown in Table 10.

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

Where:

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

Conversion factor (MPN/day) = 28,316.846 mL/ft3 * 86,400 sec/day

Table 10. Allowable loadings in impaired AUs of the Navasota River below Lake Limestone watershed

Station ID	Name	AU ID	5% Exceedance Flow (cfs)	5% Exceedance Load (Billion MPN/day)	Indicator Bacteria	TMDL (Billion MPN/day)
16398	Navasota at Grimes CR 162	1209_03	3,595.740	11,084.534	*E. coli*	11,084.534
11877	Navasota at U.S. 79	1209_05	1,135.590	3,500.666	*E. coli*	3,500.666

Margin of Safety

The MOS is applied to the allowable load in the watershed. The equation below was used to calculate the MOS for the impaired AUs in the Navasota River below Lake Limestone watershed (Table 11).

MOS = 0.05 * TMDL

Where:

MOS = margin of safety

TMDL = total maximum daily load

Table 11. Margin of safety calculations for the Navasota River below Lake Limestone watershed

Station ID	Name	AU ID	TMDL (Billion MPN/day)	Indicator Bacteria	MOS (Billion MPN/day)
16398	Navasota at Grimes CR 162	1209_03	11,084.534	*E. coli*	554.226
11877	Navasota at U.S. 79	1209_05	3,500.666	*E. coli*	175.033

Wasteload Allocation

The WLA is the sum of loads from regulated sources. This variable consists of two parts—the waste load from the allocated TPDES-regulated WWTFs (WLA_{WWTF}) and waste load that is allocated to stormwater dischargers (WLA_{SW}). The equation below is used the calculate the WLA.

$$WLA = WLA_{WWTF} + WLA_{SW}$$

WWTFs

TPDES-permitted WWTFs are allocated a daily waste load (WLA_{WWTF}) calculated as the total sum of loads from regulated WWTF loading. This is expressed in the following equation:

$$WLA_{WWTF} = \text{Criterion} * \text{Flow} * \text{Conversion Factor}$$

Where:

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

Flow = full permitted flow (MGD)

Conversion Factor (to MPN/day) = 1.54723 cfs/MGD * 28,316.846 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 12 shows the WWTFs within the TMDL watershed that contribute treated wastewater to impaired AUs 1209_03 and 1209_05. Three WWTFs discharge to the upstream impaired AU (1209_05) and are included in downstream AU (1209_03) allocations.

Table 12. Wasteload allocations for the TPDES permitted facilities within the Navasota River below Lake Limestone watershed that contribute flow to the impared AUs

TPDES Permit Number	Facility	Final Receiving AU	Final Permitted Discharges (MGD) [a]	*E. coli* WLA_{WWTF} (Billion MPN/day)[b]
WQ0013980001	City of Marquez WWTF	1209_05	0.040	0.190
WQ0010824001	City of Thornton WWTF	1209_05	0.041	0.195
WQ0014659002	Leon ISD WWTF	1209_05	0.020	0.095
			Total for Both AUs	**0.480**

[a] Permitted Flow from Table 4

[b] WLA_{WWTF} = Criterion * Flow * Conversion Factor

Stormwater

Stormwater discharges from MS4, industrial, and construction areas are considered regulated point sources. Therefore, the WLA calculations must also include an allocation for regulated stormwater discharges (WLA_{SW}). A simplified approach for estimating the WLA for these areas was used in the development of these TMDLs due to the limited amount of data available, the complexities associated with simulating rainfall runoff, and the variability of stormwater loading.

The percentage of the watershed that is regulated under the industrial and construction permits is used to estimate the amount of the overall runoff load to be allocated as the regulated stormwater contribution in the WLA_{SW} component of the TMDL. 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}. Tables 13, 14, and 15 show the results of the WLA_{SW} calculations.

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

$$WLA_{SW} = (TMDL - WLA_{WWTF} - FG - MOS) * FDA_{SWP}$$

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 regulated facilities

MOS = margin of safety

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

Table 13. Regulated stormwater calculations for AU 1209_03

MS4 General Permit (acres)	Industrial (acres)	Construction Activities (acres)	Total Area of Permits (acres)	Watershed Area (acres)	FDA_{SWP}
0	8,357.47	1,258.6	9,616.07	719,434.2	0.013

Table 14. Regulated stormwater calculations for AU 1209_05

MS4 General Permit (acres)	Industrial (acres)	Construction Activities (acres)	Total Area of Permits (acres)	Watershed Area (acres)	FDA_{SWP}
0	4,589.6	520.2	5,109.8	227,062	0.022

Urbanized areas currently regulated by an MS4 permit must implement the control measures/programs outlined in an approved SWMP. Although additional flow may occur from development or re-development, loading of the pollutant of concern should be controlled and/or reduced through the implementation of BMPs as specified in both the TPDES permit and the SWMP.

An iterative, adaptive management approach is used to address stormwater discharges. This approach encourages the implementation of structural or non-structural controls, implementation of mechanisms to evaluate the performance of the controls, and finally, allowance to make adjustments (e.g., more stringent controls or specific BMPs) as necessary to protect water quality.

Table 15. Wasteload allocations for stormwater within the Navasota River below Lake Limestone watershed that contribute flow to AU 1209_03 and AU 1209_05

AU ID	TMDL [a]	WLA_{WWTF} [b]	FG [c]	MOS [d]	FDA_{SWP} [e]	WLA_{SW}
1209_03	11,084.534	0.480	0.145	554.226	0.013	136.885
1209_05	3,500.666	0.480	0.145	175.033	0.022	73.150

[a] TMDL from Table 10

[b] WLA_{WWTF} from Table 12

[c] FG from Table 17

[d] MOS from Table 11

[e] FDA_{SWP} from Table 13 and Table 14

Implementation of WLAs

The TMDLs in this document will result in protection of existing beneficial uses and conform to Texas' antidegradation policy. The three-tiered antidegradation policy in the Texas Water Quality Standards prohibits an increase in loading that would cause or contribute to degradation of an existing use. The antidegradation policy applies to point source pollutant discharges. In general, antidegradation procedures establish a process for reviewing individual proposed actions to determine if the activity will degrade water quality.

The TCEQ intends to implement the individual WLAs through the permitting process as monitoring requirements and/or effluent limitations as required by the amendment of 30 Texas Administrative Code (30 TAC) Chapter 319, which became effective November 26, 2009. WWTFs discharging to the TMDL AUs will be assigned an effluent limit based on the TMDL. Monitoring requirements are based on permitted flow rates and are listed in 30 TAC §319.9.

The permit requirements will be implemented during the routine permit renewal process. However, there may be a more economical or technically feasible means of achieving the goal of improved water quality and circumstances may warrant changes in individual WLAs after these TMDLs are adopted. Therefore, the individual WLAs, as well as the WLAs for stormwater, are non-binding until implemented via a separate TPDES permitting action, which may involve preparation of an update to the state's WQMP. Regardless, all permitting actions will demonstrate compliance with the TMDL.

The Executive Director or Commission may establish interim effluent limits and/or monitoring-only requirements as a permit amendment or permit renewal. These interim limits will allow a permittee time to modify effluent quality in order to attain the final effluent limits necessary to meet the TCEQ and EPA-approved TMDL allocations. The duration of any interim effluent limits may not be any longer than three years from the date of permit re-issuance. New permits will not contain interim effluent limits because compliance schedules are not allowed for a new permit.

Where a TMDL has been approved, domestic WWTF TPDES permits will require conditions consistent with the requirements and assumptions of the WLAs. For NPDES/TPDES-regulated municipal, construction stormwater, and industrial stormwater discharges, water quality-based effluent limits (WQBELs) that implement the WLA for stormwater may be expressed as BMPs or other similar requirements, rather than as numeric effluent limits.

The November 26, 2014, memorandum from EPA relating to establishing WLAs for stormwater sources states:

> "Incorporating greater specificity and clarity echoes the approach first advanced by EPA in the 1996 Interim Permitting Policy, which anticipated that where necessary to address water quality concerns, permits would be modified in subsequent terms to include "more specific conditions or limitations [which] may include an integrated suite of BMPs, performance objectives, narrative standards, monitoring triggers, numeric WQBELs, action levels, etc."

Using this iterative adaptive BMP approach to the maximum extent practicable is appropriate to address the stormwater component of these TMDLs.

Updates to WLAs

These TMDLs are, by definition, the total of the sum of the WLA, the sum of the LA, and the MOS. Changes to individual WLAs may be necessary in the future in order to accommodate growth or other changing conditions. These changes to individual WLAs do not ordinarily require a revision of the TMDL document; instead, changes will be made through updates to the state's WQMP. Any future changes to effluent limitations will be addressed through the permitting process and by updating the WQMP.

Load Allocation

The LA is the remaining load from unregulated sources, and is calculated as:

$$LA = TMDL - WLA_{WWTF} - WLA_{SW} - FG - MOS$$

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 regulated facilities

MOS = margin of safety

Table 16. Load allocations for the Navasota River below Lake Limestone 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	11,084.534	0.480	136.885	0.145	554.226	10,392.798
1209_05	3,500.666	0.480	73.150	0.145	175.033	3,251.858

[a] TMDL from Table 10

[b] WLA_{WWTF} from Table 12

[c] WLA_{SW} from Table 15

[d] FG from Table 17

[e] MOS from Table 11

[f] $LA = TMDL - WLA_{WWTF} - WLA_{SW} - FG - MOS$

Allowance for Future Growth

The future growth component of the TMDL equation addresses the requirement to account for future loadings that may occur due to population growth, changes in community infrastructure, and development. Specifically, this TMDL component takes into account the probability that new flows from WWTF discharges may occur in the future. The assimilative capacity of streams increases as the amount of flow increases.

The allowance for future growth will result in protection of existing beneficial uses and conform to Texas' antidegradation policy.

Currently, there are 13 domestic WWTFs in the watershed with *E. coli* limits, but only three of them directly affect the impaired AUs in the watershed (Table 17). The City of Thornton WWTF is located in Limestone County and is within the Steele Creek subbasin. Steele Creek flows into AU 1209_05 of the Navasota River. The City of Marquez WWTF and Leon ISD WWTF are located in Leon

County and contribute 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 counties between the years of 2020 to 2070 was previously found in Table 2. The calculation results for the impaired AUs are shown in Table 17.

$$FG = Criterion * [\%POP_{2020\text{-}2070} * WWTF_{FP}] * Conversion\ Factor$$

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 = 1.54723 cfs/MGD * 28,316.846 mL/ft^3 * 86,400 s/d

Table 17. Future growth of current WWTFs in the Navasota River below Lake Limestone watershed

TPDES Permit Number	Facility	Full Permitted Flow (MGD)	Type/ Location of Outfall	Percent Population Increase (2020-2070)	2070 Permitted Flow (Future Growth) (MGD)[a]	FG *E. coli* (Billion MPN/ day) [b]
WQ0013980001	City of Marquez WWTF	0.040	Municipal/ Leon	35%	0.014	0.066
WQ0010824001	City of Thornton WWTF	0.041	Municipal/ Limestone	23.9%	0.009	0.046
WQ0014659002	Leon ISD WWTF	0.020	School/ Leon	35%	0.007	0.033
Total for AUs 1209_03 & 1209_05					**0.030**	**0.145**

[a] Significant digits based on full permitted flow

[b] $FG = Criterion * [\%POP_{2020\text{-}2070} * WWTF_{FP}] * Conversion\ Factor$

Compliance with these TMDLs is based on keeping the bacteria concentrations in the selected waters below the limits that were set as criteria for the individual sites. Future growth of existing or new point sources is not limited by these TMDLs as long as the sources do not cause bacteria to exceed the limits. The assimilative capacity of streams increases as the amount of flow increases. Consequently, increases in flow allow for increased loadings. The LDC and tables in this TMDL will guide determination of the assimilative capacity of the stream under changing conditions, including future growth.

Summary of TMDL Calculations

Table 18 summarizes the TMDL calculations for the Navasota River below Lake Limestone watershed. The TMDL was calculated based on the median value (five percent exceedance) within the high flow regime from the LDC developed for each impaired segment. Allocations are based on the geometric mean criterion for *E.coli* of 126 MPN/day and include a five percent explicit MOS.

Table 18. Final TMDL allocation summary for the Navasota River below Lake Limestone watershed

AU ID	TMDL [a]	WLA_{WWTF} [b]	WLA_{SW} [c]	LA [d]	FG [e]	MOS [f]
1209_03	11,084.534	0.480	136.885	10,392.798	0.145	554.226
1209_05	3,500.666	0.480	73.150	3,251.858	0.145	175.033

[a] TMDL from Table 10

[b] WLA_{WWTF} from Table 12

[c] WLA_{SW} from Table 15

[d] LA from Table 16

[e] FG from Table 17

[f] MOS from Table 11

The final TMDL allocations comply with the requirements of 40 CFR §130.7 and include the future growth component within the WLA_{WWTF} (Table 19).

Table 19. Final TMDL allocations for the Navasota River below Lake Limestone watershed

All loads expressed as Billion MPN/day

AU ID	TMDL [a]	WLA_{WWTF} [b]	WLA_{SW} [c]	LA [d]	MOS [e]
1209_03	11,084.534	0.625	136.885	10,392.798	554.226
1209_05	3,500.666	0.625	73.150	3,251.858	175.033

[a] TMDL from Table 10

[b] WLA_{WWTF} (Table 12) + FG (Table 17)

[c] WLA_{SW} from Table 15

[d] LA from Table 16

[e] MOS from Table 11

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

Seasonal Variation

Federal regulations [40 CFR §130.7(c)(1)] require that TMDLs account for seasonal variation in watershed conditions and pollutant loading. Seasonality was examined between warmer months (May to September) and cooler months (November to March). The transitional months of April and October were excluded from the analysis. The Wilcox Rank Sum test was used to evaluate the presence of different *E. coli* concentrations at each monitoring site between seasons. Both AUs of the Navasota River below Lake Limestone watershed exhibited statistically significant seasonal differences in *E. coli* concentration, with cool months having higher values (Table 20) at the $\alpha = 0.05$ level.

Table 20. Seasonality analysis of the *E. coli* data

AU ID	α	p-value*	Significant Difference between Warm and Cool Months
1209_03	0.05	0.001	Yes
1209_05	0.05	0.008	Yes

*p-value is the calculated probability of finding the observed, or more extreme, value given a true null hypothesis

Public Participation

The TCEQ maintains an inclusive public participation process. From the inception of the investigation, the project team sought to ensure that stakeholders were informed and involved. Communication and comments from the stakeholders in the watershed strengthen TMDL projects and their implementation.

The TCEQ and Texas Water Resources Institute (TWRI) are jointly providing coordination for public participation in this project for the development of the TMDL and Implementation Plan (I-Plan). A series of public meetings were held to inform the public of the TMDL and to engage public participation in the development of the I-Plan.

A public meeting was held in College Station on November 5, 2015 and Franklin on November 10, 2015. Additional meetings were held at both locations on February 18, 2016, July 14, 2016, December 8, 2016, December 11, 2017, and July 11, 2018. These were followed by individual meetings with stakeholders to keep them engaged. The meetings covered the development, process, and components of watershed-based plans, along with the connection to TMDLs. Notices of meetings were posted on the project webpages by TWRI and TCEQ and on the TCEQ's TMDL program online calendar. At least two weeks prior to scheduled meetings, TWRI issued direct mailings and media releases formally inviting stakeholders to attend. To ensure that absent or new stakeholders could get information about past meetings and pertinent material, the TWRI project webpage provided meeting summaries, presentations, ground rules, and documents produced for review.

Implementation and Reasonable Assurance

The issuance of TPDES permits consistent with TMDLs provides reasonable assurance that WLAs in this TMDL report will be achieved. Per federal requirements, each TMDL is included in an update to the Texas WQMP as a plan element.

The WQMP coordinates and directs the state's efforts to manage water quality and maintain or restore designated uses throughout Texas. The WQMP is continually updated with new, more specifically focused plan elements as identified in federal regulations [40 CFR §130.6(c)]. Commission adoption of a TMDL is the state's certification of the associated WQMP update.

Because the TMDL does not reflect or direct specific implementation by any single pollutant discharger, the TCEQ certifies additional elements to the WQMP after the I-Plan is approved by the Commission. Based on the TMDL and I-Plan, the TCEQ will propose and certify WQMP updates to establish required water-quality-based effluent limitations necessary for specific TPDES wastewater discharge permits.

For MS4 entities, where numeric effluent limitations are infeasible, the permits require that the MS4 develop and implement BMPs under each MCM, which are a substitute for effluent limitations, as allowed by federal rules. How a regulated MS4 meets each MCM is not prescribed in detail in the MS4 permits but is included in the permittee's SWMP. During the permit renewal process, TCEQ revises its MS4 permits as needed to require the implementation of other specific revisions in accordance with an approved TMDL and I-Plan.

Strategies for achieving pollutant loads in TMDLs from both point and nonpoint sources are reasonably assured by the state's use of an I-Plan. The TCEQ is committed to supporting the implementation of all TMDLs adopted by the Commission.

I-Plans for Texas TMDLs use an adaptive management approach that allows for the refinement or addition of methods to achieve environmental goals. This adaptive approach reasonably assures that the necessary regulatory and voluntary activities to achieve pollutant reductions will be implemented. Periodic, repeated evaluations of the effectiveness of implementation methods ascertain whether progress is occurring, and may show that the original distribution of loading among sources should be modified to increase efficiency.

I-Plans will be adapted as necessary to reflect needs identified in evaluations of progress.

Key Elements of an Implementation Plan

An I-Plan includes a detailed description and schedule of the regulatory and voluntary management measures to implement the WLAs and LAs of particular TMDLs within a reasonable time. I-Plans also identify the organizations responsible for carrying out management measures, and a plan for periodic evaluation of progress.

Strategies to optimize compliance and oversight are identified in an I-Plan when necessary. Such strategies may include additional monitoring and reporting of effluent discharge quality to evaluate and verify loading trends, adjustment of an inspection frequency or a response protocol to public complaints, and escalation of an enforcement remedy to require corrective action of a regulated entity contributing to an impairment.

The TCEQ works with stakeholders and interested governmental agencies to develop and support I-Plans and track their progress. Work on the I-Plan begins during the development of TMDLs. Because these TMDLs reference agricultural sources of pollution, the TCEQ will also work in close partnership with the TSSWCB when developing the I-Plan. The TSSWCB is the lead agency in Texas responsible for planning, implementing, and managing programs and practices for preventing and abating agricultural and silvicultural nonpoint sources of water pollution. The cooperation required to develop an I-Plan will become a cornerstone for the shared responsibility necessary to carry it out.

Ultimately, the I-Plan will identify the commitments and requirements to be implemented through specific permit actions and other means. For these reasons, the I-Plan that is approved may not approximate the predicted loadings identified category-by-category in the TMDL and its underlying assessment. The I-Plan is adaptive for this very reason; it allows for continuous update and improvement.

In most cases, it is not practical or feasible to approach all TMDL implementations as a one-time, short-term restoration effort. This is particularly true when a challenging wasteload reduction or load reduction is required by the TMDL, there is high uncertainty with the TMDL analysis, there is a need to reconsider or revise the established water quality standard, or the pollutant load reduction would require costly infrastructure and capital improvements.

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Appendix A.
The SWAT Model

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 (ET), 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 River below Lake Limestone watershed is cataloged in the sequential steps listed below.

Step 1: Watershed delineation is performed using a digital elevation model (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 to ensure the created streams contain the necessary stream network. The higher the value, the fewer cells and fewer 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 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.

Step 2: 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 run off into stream channels. The SWAT model uses the Soil Conservation Service (now NRCS) curve number method to predict runoff expected from within the watershed.

The curve number method, shown below in Equation A-1 and Equation A-2, was developed by the USDA to estimate storm runoff.

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

$$Q = \frac{(P - 0.2 \cdot S)^2}{(P - 0.8 \cdot S)}$$ (Equation A-2)

Where:

Q = runoff (in)

P = rainfall (in)

S = potential maximum retention after runoff begins (inches)

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 0.2 x S. This produces the simplified runoff curve number equation presented in Equation A-1. The S variable (calculated using Equation A-3) is described by a curve number that ranges from 0 to 100 and was based on the hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition.

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

Where:

CN = curve number

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 2,500. 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 SSURGO soils. The Cropland Data Layer and SSURGO soils were used to retain a realistic representation of the watershed.

Step 3: Weather inputs are critical for accurately estimating watershed inputs and in simulating evaporation and transpiration or ET. ET is the value simulated as an output, or a negative, from the watershed. Within the SWAT model, potential evapotranspiration (PET) uses the Priestley-Taylor method as the 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 are 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 seven stations were used. Data from all stations began on January 1, 1979, and ended April 25, 2016. There were 13,630 values for each station. If there were no data for a given date, -99 was used in replacement to indicate a null value.

Step 4: Calibration and Sensitivity Analysis was conducted using the SUFI-2 program within SWAT-CUP (Arnold 2012). The program 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 percent prediction uncertainty (95PPU). It also calculates the 2.5 percent and the 97.5 percent 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 percent for discharge. R-factor is the thickness of the 95PPU, and suggested acceptability is around 1. The NSE (Equation A-4) was used to evaluate the model compared to observed values. Using the NSE, according to Moriasi et al. (2007), a satisfactory model simulation for streamflow is an NSE value of ≥ 0.50. This was the baseline for the objective function used within SWAT-CUP.

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

(Equation A-4)

Where:

Y_i^{obs} = observation for constituent being evaluated

Y_i^{sim} = simulated value for constituent being evaluated

Y^{mean} = mean of observed data for constituent being evaluated

The SWAT model was calibrated for USGS gage 08110800 Navasota River at San Antonio Road near Bryan as it had the best long-term data record. Since the USGS data were from April 1997 to present, the data were split into calibration and validation periods (Table A-1).

Table A-1. 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 January 1, 1998 to December 31, 2008, with a two-year warm-up period. A warm-up period is recommended to allow the model simulations to stabilize model parameters and variables. Warm-up periods can range in dates depending on the variables being examined. Since this project is only examining streamflow, a short warm-up period of two to three years is sufficient (Daggupati et al., 2015).

Ten parameters were chosen to optimize the model within SWAT-CUP (Table A-2). 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 to them. Current values calculated within the model related to HRUs, such as soil and land use, were multiplied. This works 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 the groundwater and soil evaporation (ESCO parameter in Table A-2) compensation factor 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 (Table A-2).

The Navasota River below Lake Limestone 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 streamflow 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 A-2. Parameters optimized in SWAT-CUP

Parameter	Description	Default	Min	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)	1,000	0	5,000	.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	2,000	0 - .1458

Parameter	Description	Default	Min	Max	Calibrated Value
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

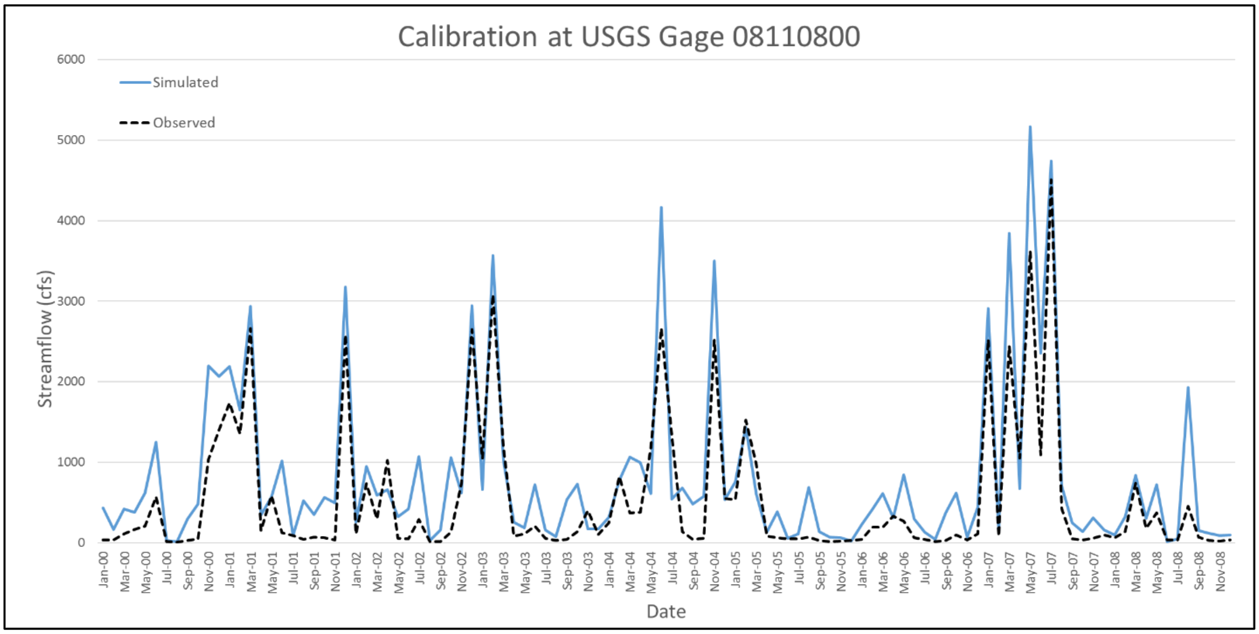

Figure A-1. Observed streamflow values plotted against SWAT simulation

The final NSE value for the calibrated subbasin was 0.69 and was above the minimum acceptance level of 0.5 (Figure A-1). Sensitivity analysis was evaluated by the t-statistic 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 parameter's space and identify parameter correlation.

SWAT-CUP best parameters were repeatedly put back into the model to achieve an objective function NSE of 0.50 or higher. The sensitivity of each parameter can be measured by looking at the t-stat values and the p-values (Table A-3). Sensitive parameters will have a higher absolute t-statistic value while significantly sensitive parameters will have p-values closer to zero. None of the parameters were particularly significantly sensitive.

Step 5: Validation of a model is necessary to check that the model is performing as expected 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 comparing observed and simulated outputs for the validated model at the USGS gages on Highway 79 near Easterly and at Old San Antonio Road were 0.79 and 0.51, respectively (Figure A-2 and Figures A-3). These values were above the approval threshold of 0.5; thus, the model was deemed acceptable.

Table A-3. Parameter global sensitivity metrics

Parameter Name	Description	t-statistic	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

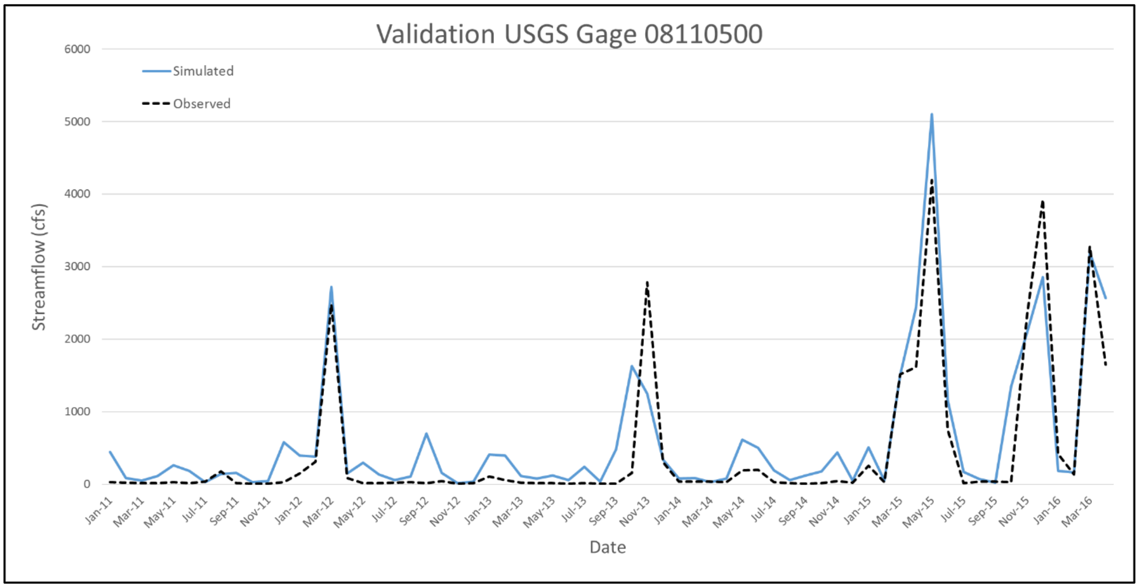

Figure A-2. Model validation for USGS gage 08110500 on the Navasota near Easterly, TX

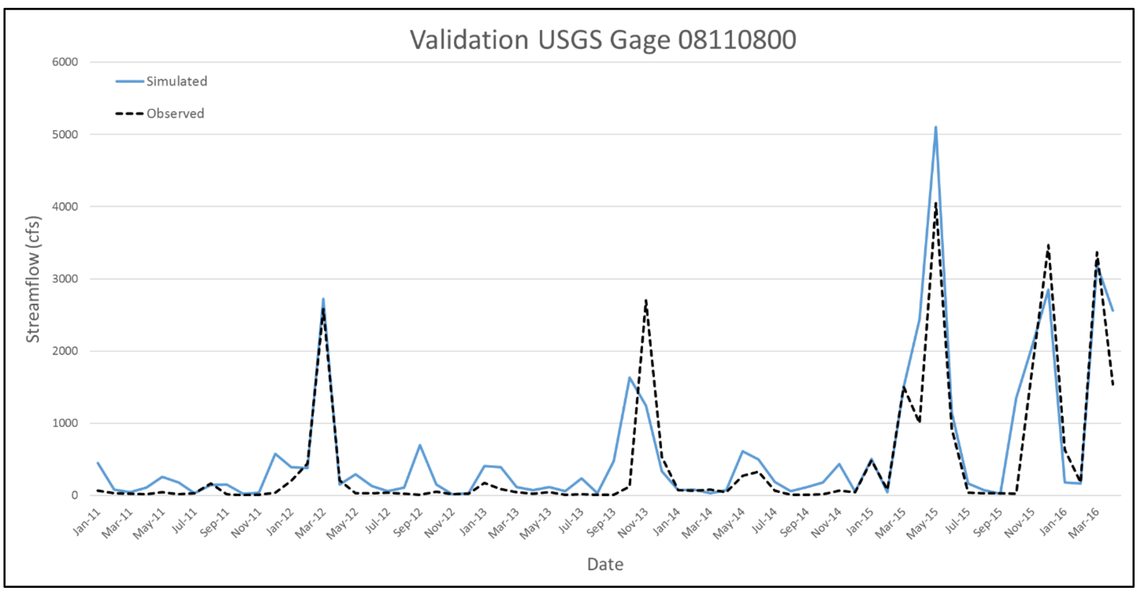

Figure A-3. Model validation for USGS gage 08110800 on the Navasota River at Old San Antonio Road near Bryan, TX

Step 6: 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, the largest source of uncertainty is usually from precipitation values due to collection measurement uncertainty from wind and ungauged 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 A-4 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 0.22 and the P-factor is 0.13 for this simulation.

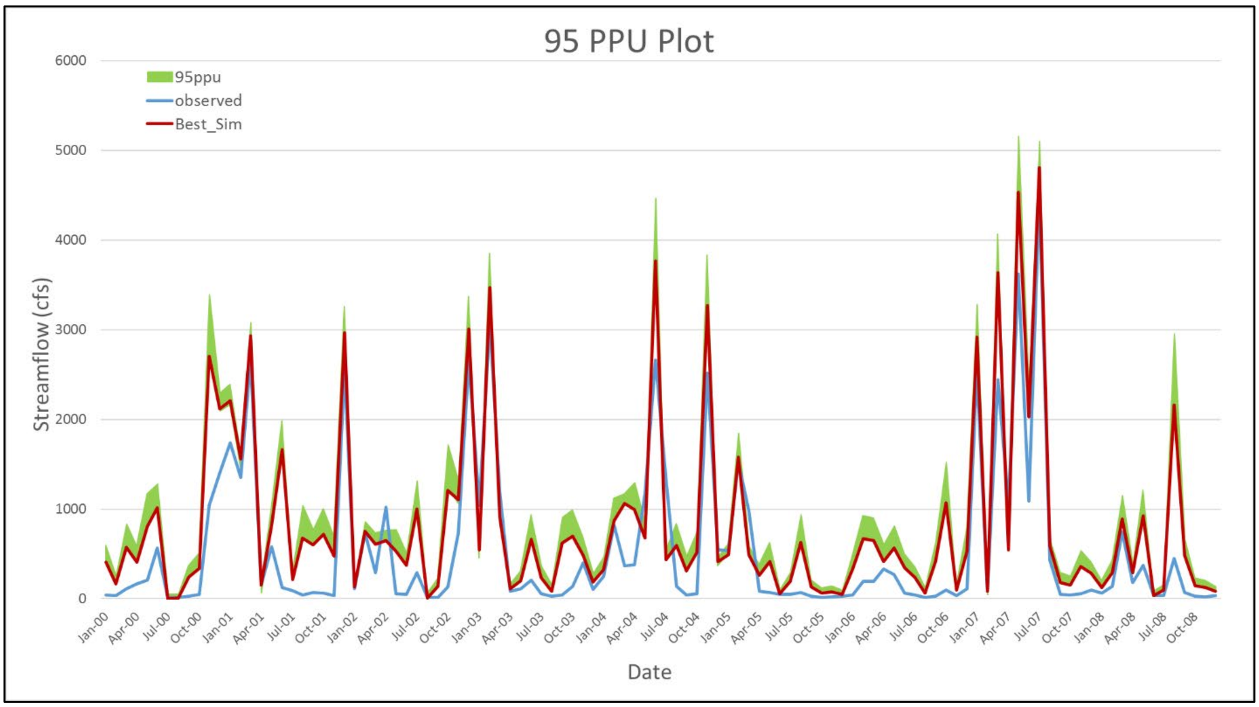

Figure A-4. 95PPU plot: the green bars show the uncertainty zones within the simulation

Appendix B. Equations for Calculating TMDL Allocations for Changed Contact Recreation Standards

The following abbreviations apply for all the equations in this appendix:

Std = revised contact recreation standard

MOS = margin of safety

LA = total load allocation (unregulated 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 B-1. Summary of allocation loads for Navasota River below Lake Limestone (AU 1209_03) at selected water quality standards (billion MPN/day)

Standard (MPN/100 mL)	TMDL	WLA_{wwtf}	WLA_{sw}	LA	MOS
126	11,084.534	0.625	136.885	10,392.798	554.226
630	55,422.670	0.625	684.425	51,963.990	2,771.130
1,030	90,611.667	0.625	1,118.981	84,957.000	4,530.578

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

TMDL = 87.97249206 * Std

MOS = 4.398619048 * Std

LA = 82.48252381 * Std

WLA_{WWTF} = 0.625

WLA_{SW} = 1.086388889 * Std

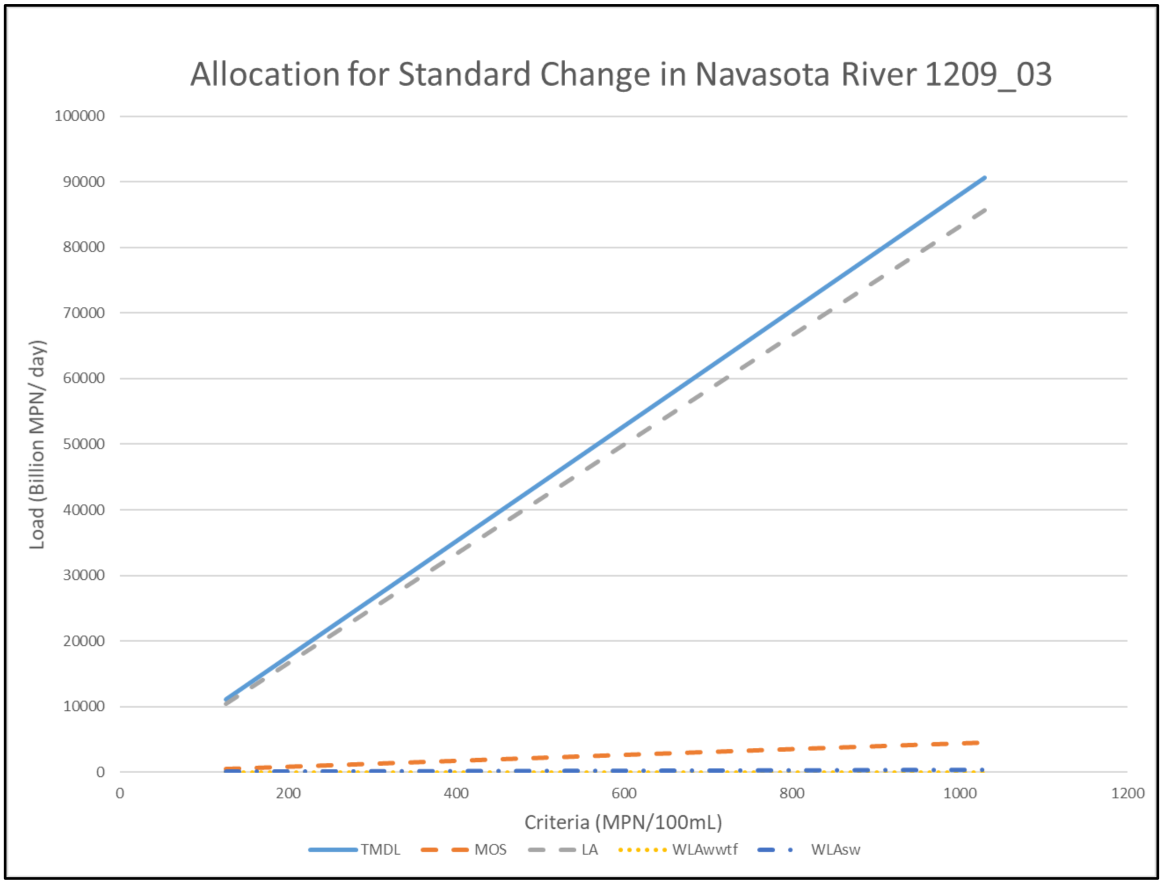

Figure B-1. Allocation loads for Navasota River (AU 1209_03) as a function of water quality criteria

Table B-2. Summary of allocation loads for Navasota River (AU 1209_05) at selected water quality standards (billion MPN/day)

Standard (MPN/100 mL)	TMDL	WLA_{wwtf}	WLA_{sw}	LA	MOS
126	3500.666	0.625	73.150	3251.858	175.033
630	17,503.330	0.625	365.750	16,259.290	875.165
1,030	28,616.555	0.625	597.972	26,582.649	1,430.825

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

$$TMDL = 27.78306349 * Std$$

$$MOS = 1.389150794 * Std$$

$$LA = 25.80839683 * Std$$

$$WLA_{WWTF} = 0.625$$

$$WLA_{SW} = 0.5805555556 * Std$$

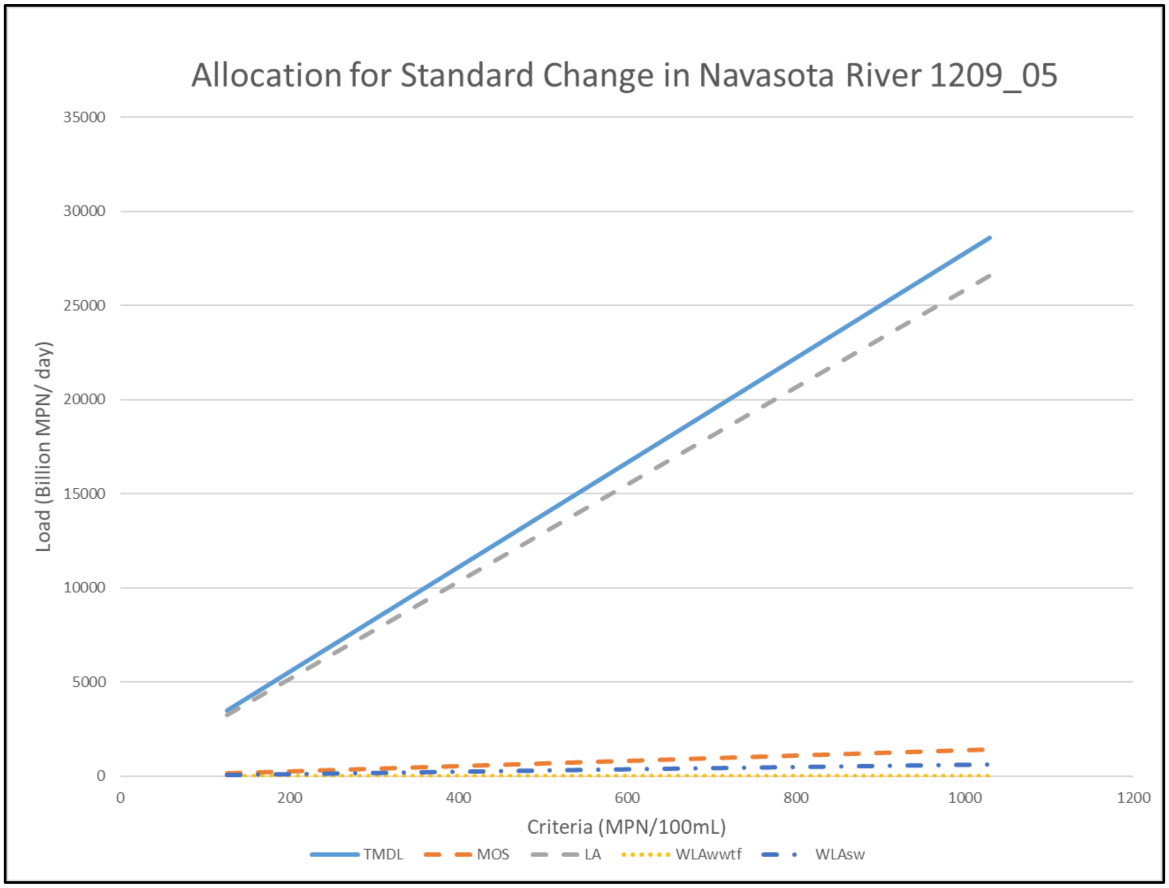

Figure B-2. Allocation loads for Navasota River (AU 1209_05) as a function of water quality criteria