Technical Support Document: Two Total Maximum Daily Loads for Indicator Bacteria in Corpus Christi Bay at Cole and Ropes Parks, Corpus Christi, Texas

Segment 2481CB
Assessment Units 2481CB_03 and 2481CB_04

Prepared for:

Texas Commission on Environmental Quality

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EXECUTIVE SUMMARY

Two beach segments of Corpus Christi Bay, Segments 2481CB_03 (Cole Park) and 2481CB_04 (Ropes Park), were placed on the 2010 Texas Water Quality Inventory and the associated list of impaired waters (Clean Water Act 303(d) List) for failing to meet the contact recreation single sample criteria of no more than 25% of the measured values exceeding 104 colony forming units (CFU) per 100 milliliters of water (104 counts/dL), for the indicator bacteria (*Enterococcus*). The Texas Commission on Environmental Quality (TCEQ) initiated the Total Maximum Daily Load (TMDL) process on these two segments to improve water quality to the point of meeting their designated contact recreation use.

Available data indicate that the major proportion of *Enterococcus* loading to Corpus Christi Bay, comes from stormwater runoff. The contributing watersheds to the stormwater outfalls in, and adjacent to, Cole and Ropes are part of the City of Corpus Christi stormwater drainage system and can be identified in the City of Corpus Christi Stormwater Master Plan (Green and West 2009) and the City of Corpus Christi Infrastructure Mapbook (City of Corpus Christi 2006). There are twelve main watersheds associated with these outfalls totaling 1787 hectares of urban land that contribute rainfall runoff to Corpus Christi Bay adjacent to the impaired segments.

There are 33 ambient surface water quality monitoring (SWQM) stations located in or near the impaired segments. However, there are no SWQM stations located in the watersheds draining to these segments. SWQM data have been collected primarily by two entities, the Texas General Land Office (TGLO) under the Texas Beach Watch Program and the Center for Coastal Studies (CCS) at Texas A&M Corpus Christi under contract to the TCEQ (Nicolau and Hill, 2011; Nicolau and Hill, 2013).

Analysis of the data shows that *Enterococcus* concentrations often exceeded the contact recreation single sample criteria, prompting the TGLO to issue "Beach Advisories" for Cole and Ropes Parks. TCEQ includes beach advisory information in the assessment process used to develop the Texas Integrated Report of Surface Water Quality (formerly known as Texas' 305[b] report and 303[d] list), identifying beaches with persistent advisories. The TCEQ assessment process consists of identifying the percentage of days each beach is under an advisory. TCEQ then categorizes the beach segments using the following scale:

Beach advisories <25% of the time—Fully Supporting

Beach advisories 20-25% of the time—Concern and Fully Supporting

Beach advisories < 20% of the time—Delisted and Fully Supporting

Beach advisories ≥ 25% of the time—Not Supporting

In 2010, the TCEQ's assessment resulted in a "Not Supporting" classification for the surface water quality segments associated with the beaches in Cole and Ropes Parks.

Further data analysis showed that there are two distinct components to the water quality impairment in these two beaches (i.e., segments), runoff from the watersheds contributing stormwater runoff to the segments and a dry weather load of unknown origin. Although, the majority of the exceedances of the contact recreation criteria occurred during, or directly after, rainfall events, surface water quality data also show the occasional occurrences of high bacteria counts during dry weather.

A numerical model was created to simulate watershed processes and predict bacteria loading to the segments from rainfall runoff. The model provided hourly output of bacteria loads and concentrations in water at the discharge point, as well as discharge volumes. There were limited calibration data available at the outfalls and so the model was also evaluated based on its ability to produce values similar in magnitude and recurrence frequency to the measured data collected by the TGLO from 2006-2013.

The calibrated model was then used to simulate average daily loadings for both segments. However, the model can only generate loadings during periods of rainfall runoff. To calculate dry weather loads, bacteria concentrations measured in the field, that were not associated with precipitation (i.e., collected more than three days after a rain event), were used to replace the zero loadings generated by the model. This produced recurrence graphs for the entire period of simulation that were very similar to a recurrence graph of the TGLO data. Since, the majority of the exceedances appear to occur during and after rainfall events and the exact nature of dry weather load is not well known, load reductions associated with the TMDL analysis were applied only to the model-generated runoff contributions for each segment.

For Cole Park (Segment 2481CB_03), a reduction of 94.4% from current average *Enterococcus* loading is required to meet the applicable contact recreation criteria with a 5% margin of safety. For Ropes Park (Segment 2481CB_04) a reduction of 73.1% from the current average daily load is necessary to meet the contact recreation criteria with the same 5% margin of safety.

TABLE OF CONTENTS

EXECUTIVE SUMMARY i
TABLE OF CONTENTS iii
LIST OF FIGURES vi
LIST OF TABLES viii
ACRONYMS AND ABBREVIATIONS ix
SECTION 1 - INTRODUCTION 1
1.1 Background 1
1.2 Objectives 2
1.3 Watershed Description 2
SECTION 2 – SUMMARY OF EXISTING DATA 4
2.1 Soils 4
2.2 Land Use 4
2.3 Precipitation 6
2.4 Wind Direction 7
2.5 Ambient Water Quality 8
2.6 Stream Flow Data 10
2.7 Seasonality 10
2.8 General Statistics of *Enterococcus* Measurements 12
SECTION 3 - PROBLEM IDENTIFICATION & WATER QUALITY TARGETS 15
3.1 Pollutant of Concern: Characteristics of Bacterial Indicators 15
3.2 TCEQ Water Quality Standards for Contact Recreation 15
3.3 Bacteria Sources 17
SECTION 4 – POLLUTANT SOURCE ASSESSMENT 20
4.1 Point Sources: NPDES/TPDES-Permitted Sources 20
4.2 Permitted Sources: NPDES/TPDES Regulated Stormwater 21
4.2.1 Corpus Christi MS4 Permit Summary 22
4.3 Permitted Sources: NPDES No-Discharge Facilities and Confined Animal Feeding Operations (CAFOs) 23
4.4 Non-permitted Sources: Unregulated Stormwater, Failing On-site Sewage Facilities (OSSFs) and Direct Deposition 23
4.5 Sanitary Sewer Overflows (SSOs) 24
4.6 Wildlife and Unmanaged Animal Contributions 25
4.7 Non-Permitted Agricultural Activities and Domesticated Animals 26

4.8 Domestic Pets 26
4.9 Bacteria Re-growth and Die-off 26
SECTION 5 – TECHNICAL APPROACH AND METHODS 28
5.1 Using Numerical Models to Develop TMDLs 28
5.2 Development of the Numerical Model 29
5.2.1 Conceptual Model 29
5.2.2 Modeling Process and Design 30
5.2.3 Data Preparation and Processing 34
5.3 Estimating Loading and Simulations 35
5.3.1 Initial simulations 36
5.3.2 Model modification and calibration 37
5.3.2.1 Modifications 37
5.3.2.2 Calibration 37
5.3.3 Model Results and Performance 38
5.3.4 Other considerations 43
5.3.4.1 Model Limitations 43
5.3.4.2 Dry weather loads 44
5.3.4.3 Combining dry weather values with simulated wet weather values 45
5.3.5 Tertiary calibration using recurrence graph curves. 46
5.4 Development of Bacteria TMDLs Using Numerical Modeling 46
5.4.1 Step 1: Estimate Current Bacteria Loadings. 47
5.4.2 Step 2: Estimate TMDL Loadings. 47
5.4.3 Step 3: Estimate Load Reductions. 47
5.4.4 Step 4: Calculate an Explicit Margin of Safety 47
5.4.5 Step 5: Estimate Load Allocation (LA). 47
5.4.5.1 Area affected by dry weather loading (DWL) 48
5.4.5.2 Volume of the DWL zone 50
5.4.5.3 Calculating an average decay rate for bacteria at Cole and Ropes Parks 50
5.4.5.4 Calculating bacteria flux from DWL 50
5.4.5.5 Load Allocation from DWL 52
5.4.6 Step 6: Calculate Waste Load Allocation (WLA). 52
SECTION 6 – TMDL CALCULATIONS 53
6.1 TMDL and Load Allocations for Segment 2481CB_03 (Cole Park). 53
6.2 TMDL and Load Allocations for Segment 2481CB_04 (Ropes Park). 54

6.3 Estimated Loading and Critical Conditions 55
6.4 Allowance for Future Growth..... 55
SECTION 7 – PUBLIC PARTICIPATION..... 56
SECTION 8 - REFERENCES 57

LIST OF FIGURES

Figure 1. Map depicting the TMDL study area. 2

Figure 2. Sub-watersheds draining to the Cole and Ropes Parks areas of Corpus Christi Bay with discharge structure locations and conduit sizes shown at the shoreline. 3

Figure 3. Soil Types in the study area. 4

Figure 4 Land Use in the study area. 5

Figure 5. Average Monthly Precipitation at Naval Air Station Corpus Christi (12929) and Corpus Christi International Airport (412015). 7

Figure 6. Dominant Wind Direction in study area. 8

Figure 7. Texas Beach Watch and TCEQ SWQM Station Locations. 9

Figure 8. Box and Whisker Plots showing variation in *Enterococcus* concentrations among sampling sites located in Cole and Ropes Parks. 13

Figure 9. Box and Whisker Plots of Sampling Events at Ropes and Cole Parks. 14

Figure 10. Correlation coefficients of water quality parameters vs. *Enterococcus* in Corpus Christi Bay. 18

Figure 11. Correlation Coefficients of water quality parameters vs. *Enterococcus* at Cole Park. 19

Figure 12. Correlation Coefficients of water quality parameters vs. *Enterococcus* at Ropes Park. 19

Figure 13. Sanitary Sewer Overflow Locations (2008-2013). 25

Figure 14. Modeled Discharge, Precipitation and Calibration Points at Brawner Parkway Outfall near Ropes Park on June 30, 2013 and July 17, 2013. 39

Figure 15. Modeled Bacteria Concentrations, Precipitation and Calibration Points at Brawner Parkway Outfall near Ropes Park on June 30, 2013 and July 17, 2013. 40

Figure 16. Modeled Discharge, Precipitation and Calibration Points at Louisiana Outfall in Cole Park on June 30 and July 17, 2013. 41

Figure 17. Modeled Bacteria Concentrations, Precipitation and Calibration Points at Louisiana Outfall in Cole Park on June 30 and July 17, 2013. 42

Figure 18. Modeled Discharge, Precipitation and Calibration Points at Ropes Outfall in Ropes Park on July 17, 2013. 43

Figure 19. Recurrence graph of a synthetic WQM station representing all WQM stations at Cole Park. 44

Figure 20. Recurrence graph showing the combination of modeled bacteria concentrations and measured dry weather bacteria concentrations at Cole Park. 45

Figure 21. Recurrence graph showing the combination of modeled bacteria concentrations and measured dry weather bacteria concentrations at Ropes Park. 46

Figure 22. Box and whisker plot of *Enterococcus* concentrations during dry weather by water depth; collected by CCS at their Cole Park SWQM stations. 48

Figure 23. Dry weather loading zones in Cole and Ropes Parks (2008-2009 Texas Orthoimagery.). 49

Figure 24. Recurrence graph showing the load reduction necessary for the Cole Park watershed. 53

Figure 25. Recurrence graph showing the load reduction necessary for the Ropes Park watershed. 54

LIST OF TABLES

Table 1. Land Use Summary. 6

Table 2. Annual Totals at Rainfall Gages near the study area. 7

Table 3. Historical Water Quality Data (*Enterococcus*) from Beach Watch Program (2003-2013). 9

Table 4. Historical Water Quality Data (*Enterococcus*) collected by the Center for Coastal Studies (2011-2013). 10

Table 5. Maximum, Minimum and Mean Daily Temperatures by Month for Naval Air Station, Corpus Christi, TX (2003-2013) 11

Table 6. Seasonal Differences for Indicator Bacteria (*Enterococcus*) Concentrations (Warm vs. Cool Months). 12

Table 7. Seasonal Differences for Indicator Bacteria (*Enterococcus*) Concentrations (Wet vs. Dry Months). 12

Table 8. Synopsis of Texas Integrated Report for Waterbodies in the study area 16

Table 9. Water Quality Monitoring Stations Used for 303(d) Listing Decision. 16

Table 10. Percentage of Permitted Stormwater in each Watershed. 22

Table 11. Sanitary Sewer Overflow (SSO) Summary for the study area. 24

Table 12. Estimated Numbers of Pets in the TMDL Sub-watersheds. 26

Table 13. Estimated Fecal Coliform Daily Production by Pets in the TMDL Sub-watersheds 26

Table 14. Land Use code and associated American Society of Civil Engineers (ASCE) runoff coefficients for grid incorporation 31

Table 15. Event Concentration values (counts/dL) as applied in gridded dataset for initial loading calculations 35

Table 16. Decay rates calculated from data pairs collected at Cole and Ropes Parks where Co is the decay rate original concentration and Cd is the decayed concentration over one day at the same station. 51

ACRONYMS AND ABBREVIATIONS

ASAE	American Society of Agricultural Engineers
ASCE	American Society of Civil Engineers
CAFO	Concentrated Animal Feeding Operation
CCS	Center for Coastal Studies
CFR	Code of Federal Regulations
cfs	Cubic Feet Per Second
CFU	Colony Forming Unit
dL	Deciliter
DO	Dissolved Oxygen
DWL	Dry Weather Load
E. coli	*Escherichia coli*
EMC	Event Mean Concentration
GIS	Geographic Information System
GPS	Global Positioning System
LA	Load Allocation
IQR	Interquartile range
mL	Milliliter
MOS	Margin Of Safety
MPN	Most Probable Number
MS4	Municipal Separate Storm Sewer System
NCDC	National Climate Data Center
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
NPS	Nonpoint Sources
NRCS	National Resource Conservation Service
OSSF	On-Site Sewage Facility
RMSE	Root Mean Square Error
SSO	Sanitary Sewer Overflow
SWQS	Surface Water Quality Standards
TAC	Texas Administrative Code
TCEQ	Texas Commission on Environmental Quality

TGLO	Texas General Land Office
TMDL	Total Maximum Daily Loads
TPDES	Texas Pollution Discharge Elimination System
USEPA	U.S. Environmental Protection Agency
WLA	Waste Load Allocation
SWQM	Surface Water Quality Monitoring
WWTF	Wastewater Treatment Facility

SECTION 1
INTRODUCTION

1.1 Background

The federal Clean Water Act (CWA) was passed into law by the United States Congress in 1972. The Act outlined the need for states and territories to develop surface water quality standards to ensure the health and safety of the public. In Texas, these standards are detailed in Texas Administrative Code (TAC), Title 30, Chapter 307. The Texas Surface Water Quality Standards deal primarily with the concentration limits of anthropogenic pollutants that may be allowed in the state's water bodies.

Under the CWA, each state is required to periodically evaluate waters within their jurisdiction to assess attainment of designated uses, as described in their surface water quality standards, and to create a list (commonly known as the 303(d) list of impaired waters) of those water bodies that do not support their designated uses. States are required by the CWA to initiate a Total Maximum Daily Load (TMDL) for all impaired water bodies. The purpose of a TMDL is to determine the maximum amount or load of a pollutant that a water body can receive while still supporting its designated uses. The end goal of a TMDL is attainment of water quality standards by allocating the allowable load among all potential sources.

The Texas Commission on Environmental Quality (TCEQ) is responsible for the identification and restoration of all surface waters of the state of Texas that do not meet the Texas Surface Water Quality Standards. As part of this responsibility, the TCEQ establishes TMDLs for all impaired waters in the state of Texas. The TCEQ also works with local stakeholders to develop TMDL implementation plans to address excess pollutant loading in the impaired water bodies.

In 2008, based on data collected by the Texas General Land Office (TGLO) under the Texas Beach Watch Program, USEPA asked the State of Texas to list Corpus Christi Bay (Segment 2481) on the state's 303(d) List of Impaired Waters for not meeting the contact recreation single sample criteria of no more than 25% of the measured values exceeding 104 CFU/100ml (104 counts/dL), for the indicator bacteria (*Enterococcus*). USEPA subsequently asked TCEQ to list the entire Corpus Christi Bay water body in Category 5a, meaning a TMDL would be scheduled.

Upon request by TCEQ, USEPA reconsidered its initial request for listing the entire Corpus Christi Bay segment and agreed to limit the listing to include only the beach fronts at Cole Park and Ropes Park (Figure 1). USEPA also endorsed designation of the two beaches as separate assessment units (Segment 2481CB_03 and 2481CB_04, respectively) and endorsed changing the listing from category 5a to 5c; meaning additional bacteria data were needed before a TMDL can be conducted. In 2010, both Cole Park and Ropes Park were place on the Texas 303(d) List of Impaired Waters in Category 5a, and a TMDL was scheduled.

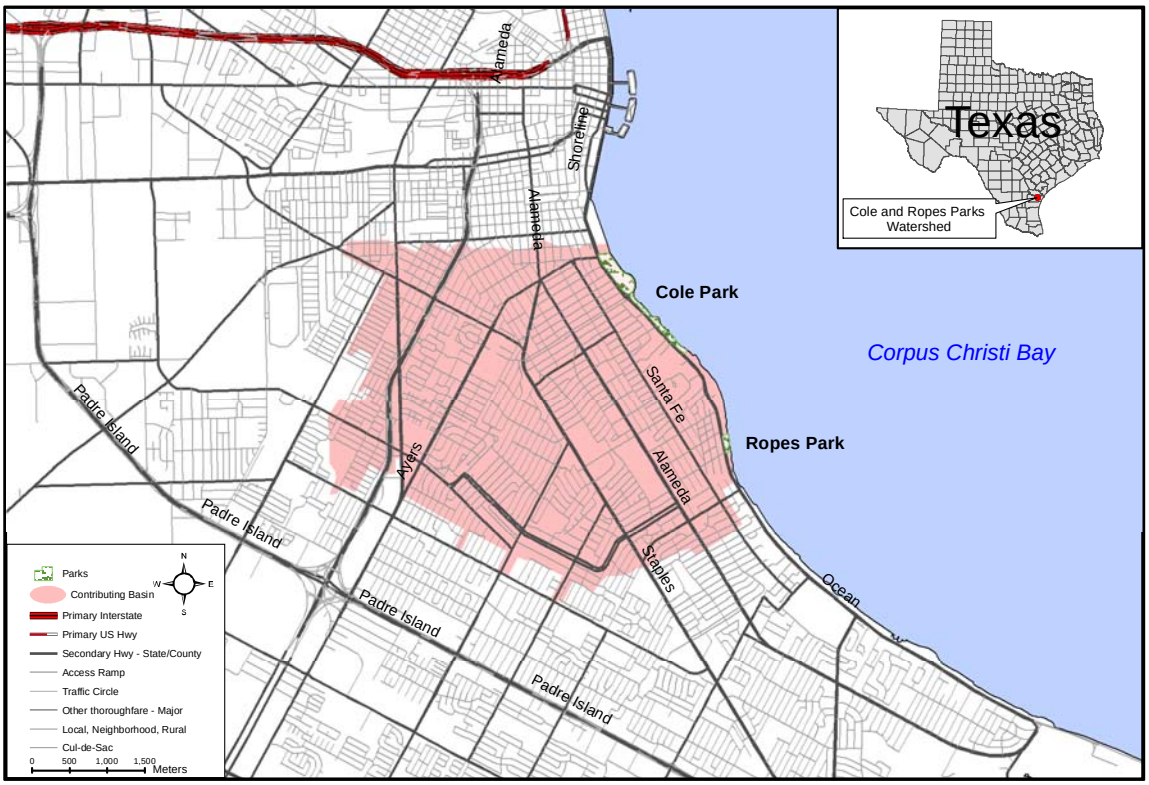


Figure 1. Map depicting the TMDL study area.

1.2 Objectives

The TCEQ initiated the TMDL process on Segments 2481CB_03 and 2481CB_04 to improve water quality to the point of meeting the designated contact recreation use of these two segments. The TMDL process consists of three parts: (1) determination of the current pollutant loadings, (2) determination of allowable pollutant loadings and (3) determination of pollutant load reductions needed to meet the impaired use(s).

The objectives of this document are to (1) present an analysis of the soils, land use meteorological, and surface water quality data available for the TMDL watersheds, (2) present information that characterizes potential pollutant sources in the TMDL watersheds, (3) document the development of a numerical model of the watershed processes that contribute pollutants to the impaired segments, and (4) present an analysis of total maximum pollutant loading limits and pollutant loads allocations.

1.3 Watershed Description

The watersheds that contribute rainfall runoff to Cole and Ropes Parks (impaired Segments 2481CB_03 and 2481CB_04 of Corpus Christi Bay) are part of the City of Corpus Christi stormwater drainage system and can be identified in the City of Corpus Christi Stormwater Master Plan (Green and West, 2009) and the City of Corpus Christi Infrastructure Mapbook (City of Corpus Christi, 2006).

There are twelve main sub-watersheds totaling 1787 hectares of urban land that discharge to Corpus Christi Bay at, and adjacent to, the impaired segments (Figure 2). These sub-watersheds range in size from 3 hectares to 826 hectares, with the two largest sub-watersheds (Louisiana Parkway - ID 220 and Brawner Parkway - ID 103) comprising 90% of the contributing area. The remaining 10 watersheds drain small areas of land immediately adjacent to Corpus Christi Bay. None of the channels draining the sub-watersheds are gauged to measure discharge and all are located within the City of Corpus Christi.

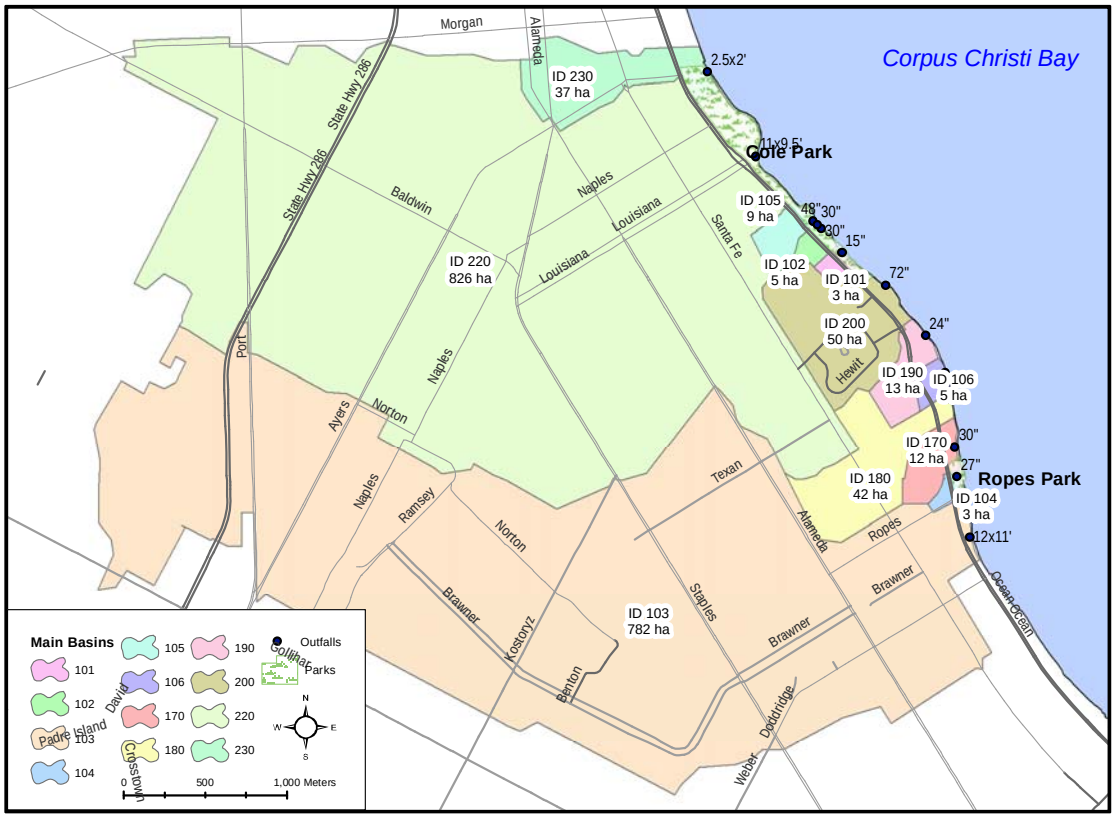


Figure 2. Sub-watersheds draining to the Cole and Ropes Parks areas of Corpus Christi Bay with discharge structure locations and conduit sizes shown at the shoreline.

SECTION 2
SUMMARY OF EXISTING DATA

The following subsections summarize the existing data relevant to the characterization of the TMDL watersheds, including soils, land use, and meteorological data in the TMDL watersheds, as well as the water quality data collected in the impaired segments. There are no associated flow data available for analysis, as the channels draining the TMDL watersheds are not gaged and the impaired receiving water bodies are marine beach segments.

2.1 Soils

The predominant soil type for Nueces County is the Victoria Series. It can be characterized as a rich clayey loam with some sandy areas. The Victoria Series has strong shrink/swell characteristics. During lengthy dry periods the soil will present large, wide cracks. During wet periods the soil is able to absorb large quantities of water (NRCS, 2005). However, as can be seen in Figure 3, the majority of the study area is underlain by built-up urban cover, which strongly influences the runoff characteristics, and is described in detail in Section 2.2.

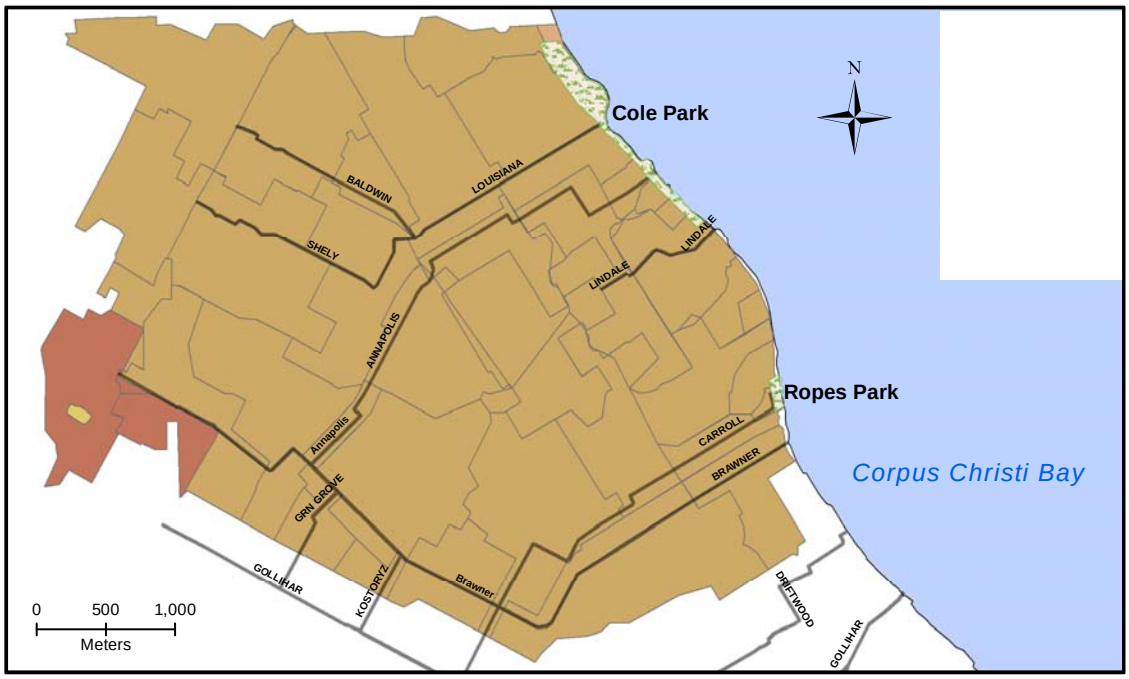


Figure 3. Soil Types in the study area.

2.2 Land Use

The study area is located in a heavily urbanized land use environment. Figure 4 and Table 1 summarize the land use areas and the corresponding percentages of each land use category present in the study area. The land use/land cover data were supplied by the City of Corpus Christi, based on property descriptions. The largest single land use in the study area is low density residential, which accounts for 47% of the total

watershed area. Transportation (roads and highways) make up the second largest land use category in the study area (24.6%).

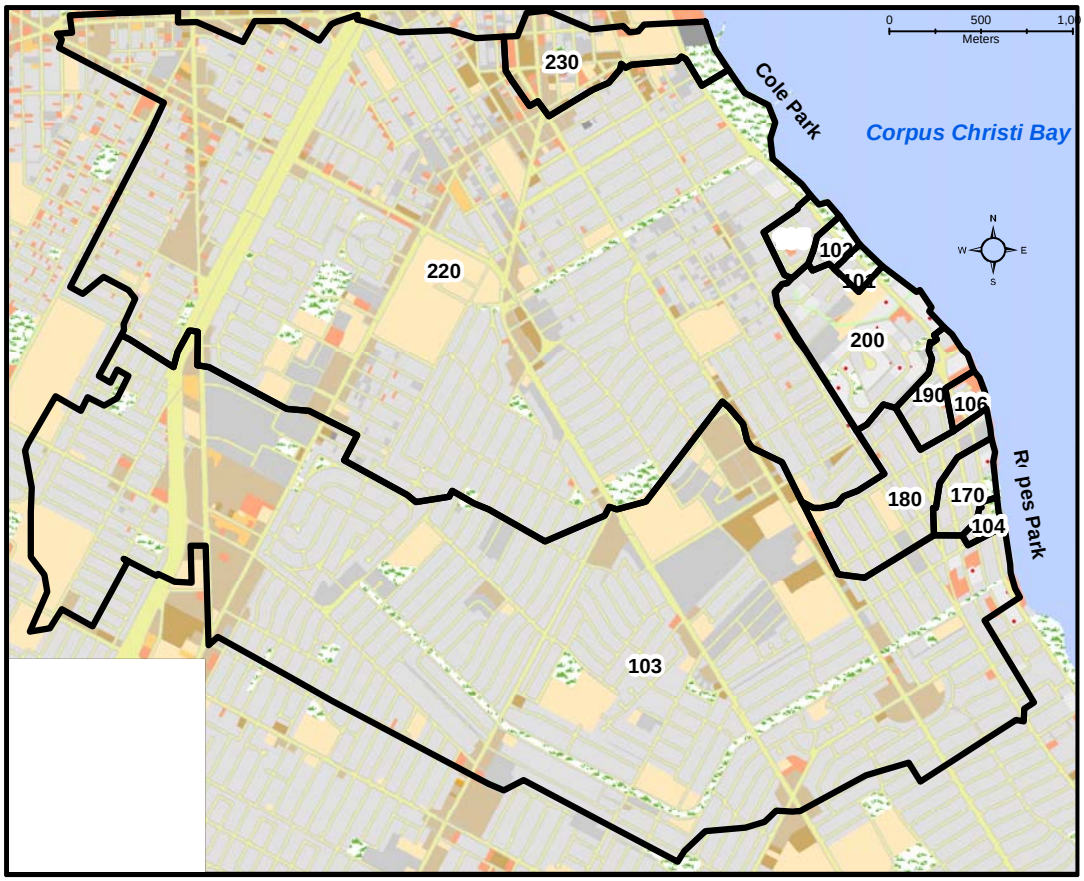


Figure 4 Land Use in the study area.

Table 1. Land Use Summary.

Land Use Description	TAG	Acres	Hectares	Percentage
Public	PSP	346.78	140	7.79%
Commercial	COM	261.73	106	5.88%
Transportation	TRANS	1096.75	444	24.64%
Light Industry	LI	14.48	6	0.33%
Vacant	VAC	65.11	26	1.46%
Professional Offices	PO	65.21	26	1.47%
Middle Density Residential	MDR	278.33	113	6.25%
Low Density Residential	LDR	2093.52	847	47.04%
High Density Residential	HDR	5.82	2	0.13%
Parks	PARK	153.42	62	3.45%
Estate Residential	ER	66.52	27	1.49%
Ditch/Culvert	DC	2.85	1	0.06%
Total		4450.83	1801	100.00%

2.3 Precipitation

There are two rain gauges located near the study area that are part of the National Weather Service's meteorological network. One meteorological station is located at Naval Air Station-Corpus Christi (ID 12926), which is located a short distance east of the study area, and the other station is at the Corpus Christi International Airport (ID 412015) which is located west of the study area. Monthly precipitation averages at both sites show a bimodal distribution with rainy periods occurring in the May/June and September/October periods (Figure 5).

Annual rainfall over the 2005-2013 period at Naval Air Station-Corpus Christi varied from a low of 7.97 inches in 2006 to a high of 43.48 inches in 2007 (Table 2). Average annual precipitation for period of record at this station is 30.27 inches. Annual rainfall over the same period at Corpus Christi International Airport ranged from a low of 12.07 inches in 2011 to a high of 43.94 inches in 2010 (Table 2). Average annual precipitation for the period of record at this station is 29.98 inches.

Precipitation events in the study area are generally of short duration. Analysis of eight years (2006-2013) of NEXRAD hourly precipitation depths over the study area indicate that 96% of the precipitation occurred over only 2.4% of this time period. This is equivalent to nine days of rain at 2.3 inches per day each year.

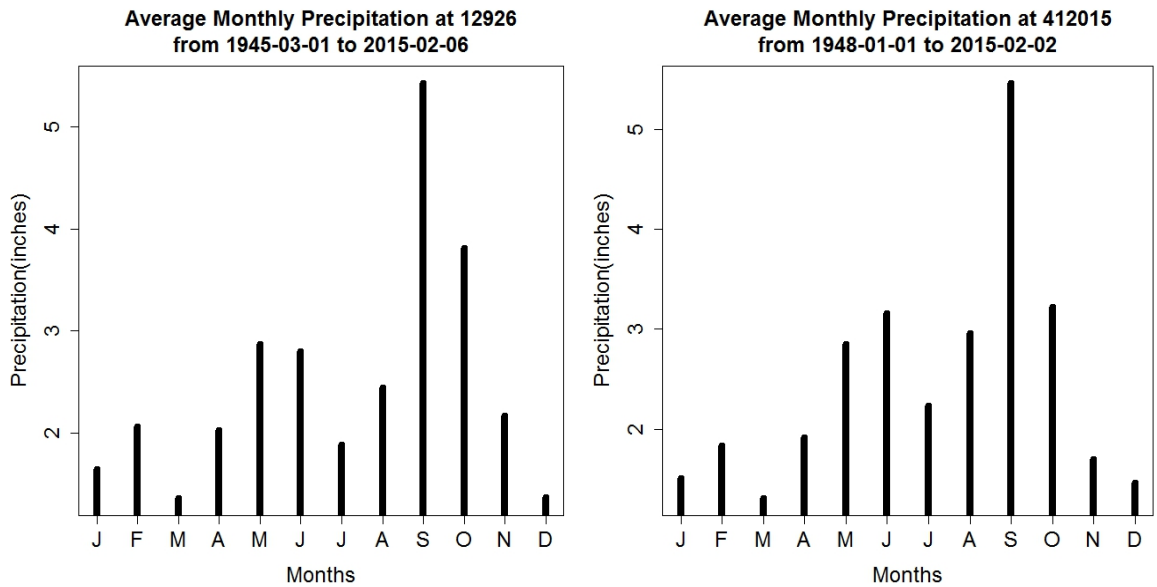


Figure 5. Average Monthly Precipitation at Naval Air Station Corpus Christi (12929) and Corpus Christi International Airport (412015).

Table 2. Annual Totals at Rainfall Gages near the study area.

Year	NAS (12926)	CCIA (412015)
2005	22.51	25.33
2006	7.97	33.94
2007	43.48	41.54
2008	26.39	28.01
2009	22.10	20.61
2010	26.00	43.94
2011	8.17	12.07
2012	22.55	18.84
2013	23.22	23.47

2.4 Wind Direction

The dominant wind direction in the study area is from the southeast. This provides a slightly onshore but mostly longshore current forcing at Ropes Park and a mostly longshore forcing at Cole Park (Figure 6). In the absence of other forcing's this would tend to drive water along the coastline in a northwesterly direction or, looking out from shore, it would tend to move water from right to left.

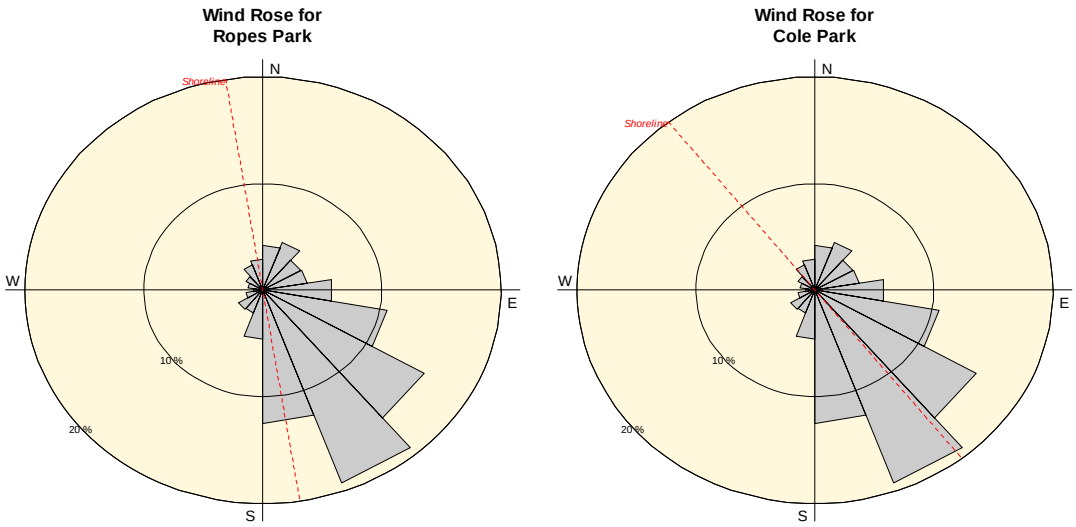


Figure 6. Dominant Wind Direction in study area.

2.5 Ambient Water Quality

There are 33 ambient SWQM stations located in, or near, the impaired segments (Figure 7), however there are no SWQM stations located in the watersheds draining to these segments. Data has been collected primarily by two entities, the TGLO under the Texas Beach Watch Program and the Center for Coastal Studies (CCS) of Texas A&M University Corpus Christi under contract to the TCEQ (Nicolau and Hill, 2011; Nicolau and Hill, 2013).

Historical ambient water quality data for indicator bacteria that have been collected by the TGLO (2003-2013) are summarized in Table 3 for 7 selected SWQM stations. Data from 20 selected SWQM stations sampled by CCS (2011-2013) are summarized in Table 4. Data for the six remaining stations depicted in Figure 7 are not presented due to low number of sampling events or due to sampling bias (i.e. collected directly in the stormwater drain).

At Cole Park (Segment 2481CB_03), TGLO measurements of bacteria concentrations (Table 3) indicate that three of the four stations exceed the water quality criteria (i.e., 104 counts/dL for more than 25% of the samples). At Ropes Park (Segment 2481CB_04) all three TGLO stations exceed the water quality criteria (Table 3). CCS water quality data collected between 2011 and 2013 also show similar water quality criteria exceedances for the same segments; most notably in stations located in the vicinity of Ropes Park (Table 4).

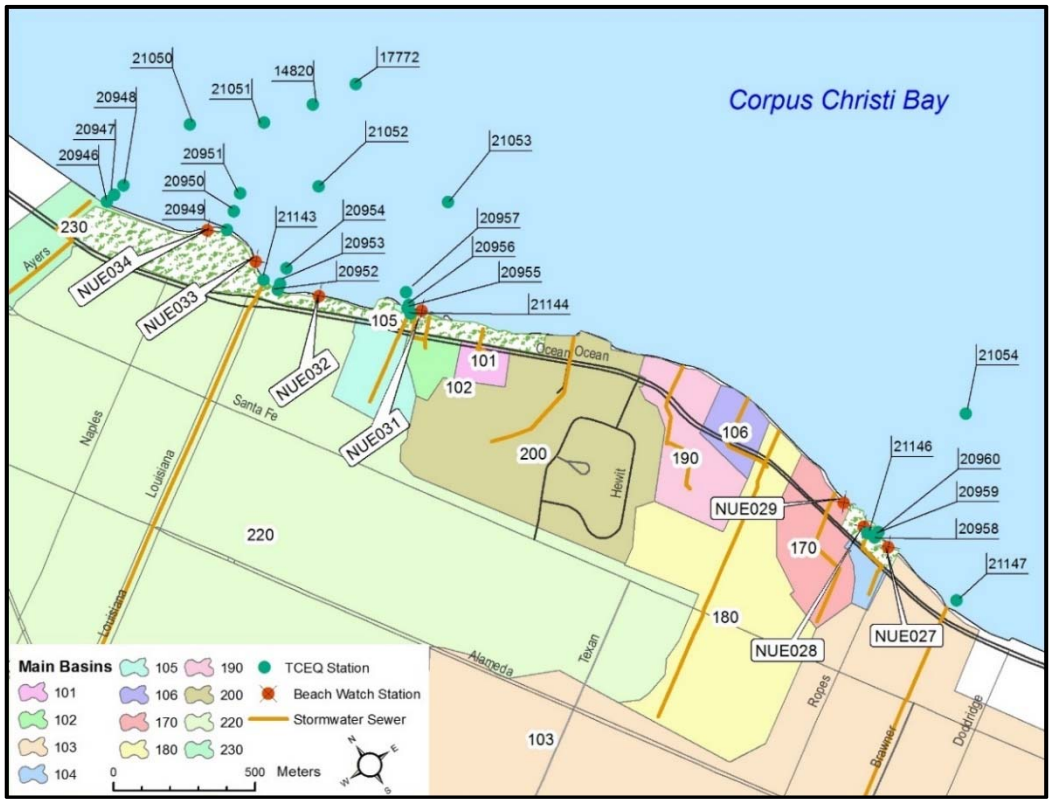


Figure 7. Texas Beach Watch and TCEQ SWQM Station Locations.

Table 3. Historical Water Quality Data (*Enterococcus*) from Beach Watch Program (2003-2013).

Segment	Station ID	TMDL Watershed	Median	Mean	% of Samples > 104 CFU/100 ml	Geometric Mean
2481CB_03	NUE034	Cole Park	24.0	227.7	22.01	24.65
2481CB_03	NUE033	Cole Park	40.0	351.8	31.76	42.55
2481CB_03	NUE032	Cole Park	34.0	296.6	31.82	37.83
2481CB_03	NUE031	Cole Park	38.0	283.7	33.83	40.39
2481CB_04	NUE029	Ropes Park	46.0	271.5	33.33	48.91
2481CB_04	NUE028	Ropes Park	46.0	284.2	34.55	52.36
2481CB_04	NUE027	Ropes Park	49.5	341.0	35.79	55.93

Table 4. Historical Water Quality Data (*Enterococcus*) collected by the Center for Coastal Studies (2011-2013).

Segment	Station ID	TMDL Watershed	Distance from Shore (m)*	Number of Samples	Number Exceeding Criteria	% of Samples >104 CFU/100 ml
2481CB_03	20952	Cole Park	5	102	32	31.4%
2481CB_03	20953	Cole Park	30	103	20	19.4%
2481CB_03	20954	Cole Park	90	103	15	14.6%
2481CB_03	21052	Cole Park	400	14	2	14.3%
2481CB_03	20955	Cole Park	4	103	31	30.1%
2481CB_03	20956	Cole Park	16	103	23	22.3%
2481CB_03	20957	Cole Park	88	103	16	15.5%
2481CB_03	21053	Cole Park	400	14	2	14.3%
2481CB_03	20946	Cole Park	4	83	10	12.0%
2481CB_03	20947	Cole Park	40	83	8	9.6%
2481CB_03	20948	Cole Park	90	83	5	6.0%
2481CB_03	21050	Cole Park	400	8	1	12.5%
2481CB_03	20949	Cole Park	0	61	7	11.5%
2481CB_03	20950	Cole Park	70	61	4	6.6%
2481CB_03	20951	Cole Park	140	61	4	6.6%
2481CB_03	21051	Cole Park	400	6	1	16.7%
2481CB_04	20958	Ropes Park	4	103	26	25.2%
2481CB_04	20959	Ropes Park	16	103	23	22.3%
2481CB_04	20960	Ropes Park	26	103	23	22.3%
2481CB_04	21054	Ropes Park	550	14	4	28.6%

** Distance approximate since actual sampling location is depth based (0.5m, 1.0m, 1.5m).*

2.6 Stream Flow Data

There are no gaged channels in the TMDL watersheds. In this report, numerical modeling is used to simulate discharge using instantaneous field measurements to calibrate the watershed model. No other historical flow data were available during water quality sample collection to assist in characterizing discharge.

2.7 Seasonality

Seasonal differences in indicator bacteria concentrations were assessed by comparing historical bacteria concentrations collected in the warmer months versus those collected during the cooler months. The monthly average temperatures for Corpus Christi (NCDC, 2005) were calculated based on observations at Naval Air Station – Corpus Christi (12926). The data were divided into warmer (>25°C) and cooler months (<17°C) with December, January, and February representing the cooler

months and May, June, July, August, and September representing the warmer months (Table 5).

Table 5. Maximum, Minimum and Mean Daily Temperatures by Month for Naval Air Station, Corpus Christi, TX (2003-2013)

Month	Daily Max (ºC)	Daily Min (ºC)	Daily Mean (ºC)	Classification
Jan	18.9	11.1	15.1	Cool
Feb	20.4	12.8	16.7	Cool
Mar	23.9	16.2	20.0	
Apr	26.9	19.7	23.1	
May	29.3	22.9	25.9	Warm
Jun	32.1	25.6	28.7	Warm
Jul	32.4	26.1	29.1	Warm
Aug	33.3	26.5	29.7	Warm
Sep	31.8	24.5	28.0	Warm
Oct	28.5	20.8	24.5	
Nov	24.3	16.4	20.4	
Dec	20.0	12.2	16.2	Cool

Note: Temperature values from NOAA (degrees Fahrenheit) have been converted to degrees Celsius.

The data were also evaluated based on wet and dry seasonality. As previously shown in Figure 5, May, June, September, and October were classified as wet months and the dry months were January, February, March, April, November and December.

A Welch t-test was conducted on log transformed bacteria values between the warmer months and cooler months as well as for dry versus wet months using TGLO data. The geometric mean was then calculated for seasonal comparison. Table 6 shows a temperature-based seasonal variation for eight TGLO stations for indicator bacteria and Table 7 shows precipitation-based seasonal variation for the same SWQM stations.

A quantile-quantile plot (Q-Q plot) was used to establish that the bacteria concentration measurements represent a log normal distribution. A log transform of the measurement thus produces a data set with a normal distribution allowing standard statistical techniques to be used. Only two SWQM stations (both located in Segment 2481CB_04 – Ropes Park) show a statistically significant difference in seasonality (p-value <0.05). Stations NUE028 and NUE029 show statistically significantly higher bacteria geomeans during warm and wet months (Table 6 and Table 7).

Table 6. Seasonal Differences for Indicator Bacteria (*Enterococcus*) Concentrations (Warm vs. Cool Months).

Station ID	Warm		Cool		p-value
	n	GeoMean	n	GeoMean	
21TXBCH-NUE027	117	42.5	20	24.0	0.167
21TXBCH-NUE028	528	57.5	108	23.6	0.000013
21TXBCH-NUE029	510	52.6	114	24.2	0.0002
21TXBCH-NUE030	97	27.0	14.0	10.2	0.09
21TXBCH-NUE031	498	35.8	138	41.2	0.49
21TXBCH-NUE032	454	31.4	111	29.9	0.81
21TXBCH-NUE033	497	40.9	113	35.0	0.46
21TXBCH-NUE034	98	14.7	16	24.0	0.32

n = number of samples
Highlighted rows correspond to stations for which the warm and cold datasets are significantly different at a 95% confidence interval. p-value is based on a t-test conducted at each station using log transformed single sample concentrations. All concentrations are in cfu/dL or MPN/dL, which are assumed to be equivalent.

Table 7. Seasonal Differences for Indicator Bacteria (*Enterococcus*) Concentrations (Wet vs. Dry Months).

Station ID	Dry		Wet		p-value
	n	GeoMean	n	GeoMean	
21TXBCH-NUE027	63	89.9	89	70.2	0.43
21TXBCH-NUE028	277	37.4	405	77.5	0.000001
21TXBCH-NUE029	281	38.9	379	63.5	0.001
21TXBCH-NUE030	51	58.5	78	50.7	0.72
21TXBCH-NUE031	322	47.4	351	45.1	0.76
21TXBCH-NUE032	293	48.3	331	38.9	0.18
21TXBCH-NUE033	287	45.6	355	44.4	0.87
21TXBCH-NUE034	51	76.0	55	36.2	0.22

n = number of samples
Highlighted rows correspond to stations for which the dry and wet datasets are significantly different at a 95% confidence interval. p-value is based on a t-test conducted at each station using log transformed single sample concentrations. All concentrations are in cfu/dL or MPN/dL, which are assumed to be equivalent.

2.8 General Statistics of *Enterococcus* Measurements

Box and whisker plots are a convenient way to demonstrate statistical similarities and differences in field measurements. Figure 8 shows box and whisker plots of *Enterococcus* concentrations measured at the Cole and Ropes Parks SWQM stations by the TGLO Beach Watch Program. Key representations made by this type of plot are the median value (represented by the thick black line within the yellow boxes), and the interquartile range (the yellow box) which bounds the values occurring between

the 25th and 75th percentiles for each station. Comparing the graphs in Figure 8, it is readily apparent that the interquartile range (IQR) of the values at Cole Park have a much greater spread than those measured at Ropes Park. This indicates that measurements made at the Ropes Park stations had similar values whereas the measurements made at Cole Park had a much greater range of values, in some cases more than one order of magnitude.

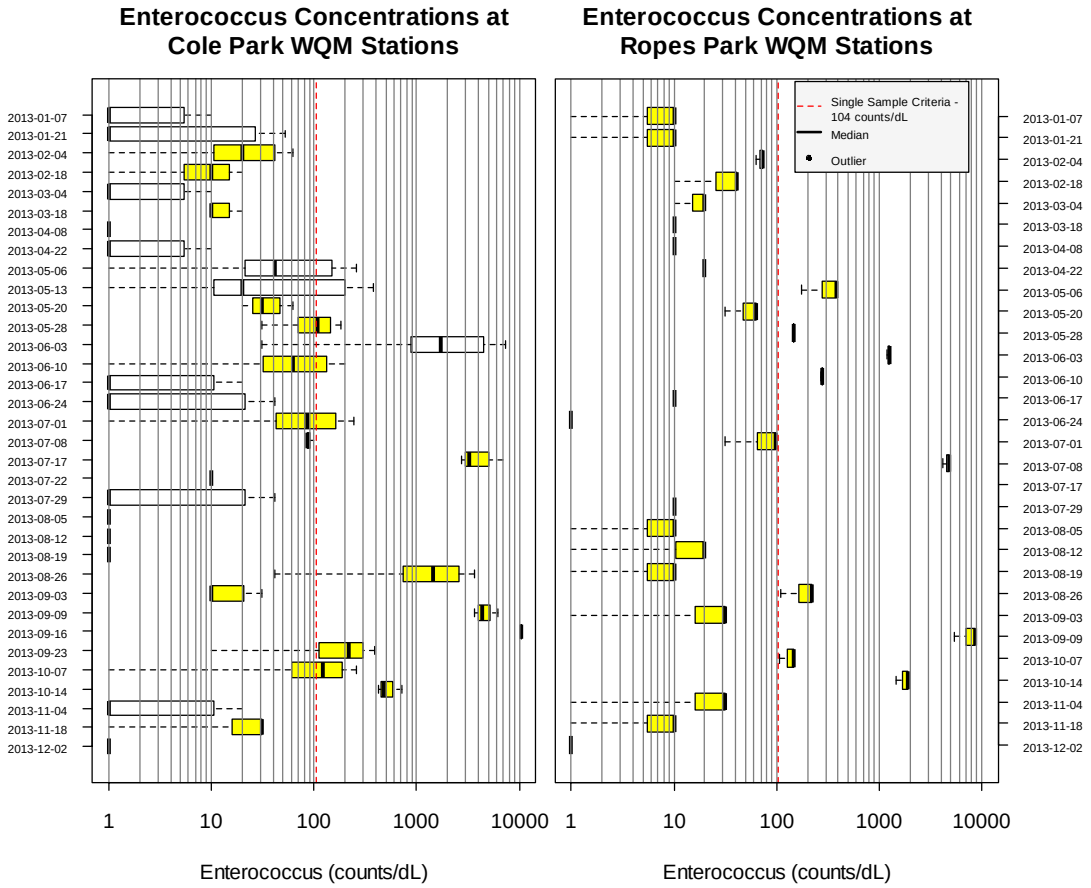
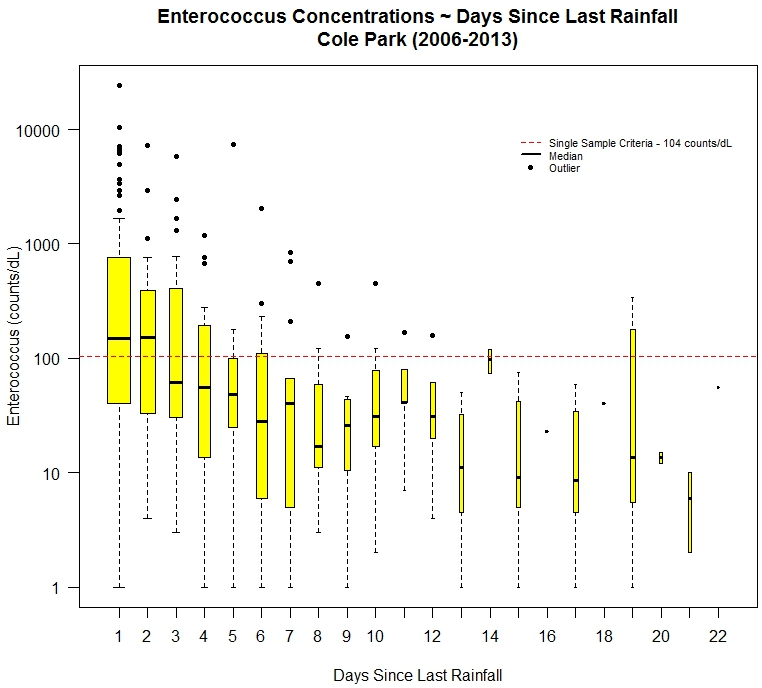


Figure 8. Box and Whisker Plots showing variation in *Enterococcus* concentrations among sampling sites located in Cole and Ropes Parks (34 monitoring events).

Figure 9 demonstrates the relationship between *Enterococcus* concentrations and days since the last rain event. In these graphs there are two additional features that are relevant. The black dots represent outliers (i.e., values that are more than 1.5 times the IQR, below the first quartile or above the third quartile) and the thickness of the IQR reflects the number of measurements in the evaluation. The graphs show that the highest *Enterococcus* concentrations occur directly after rainfall events. However, it is also evident that *Enterococcus* concentrations can be elevated (exceeding single sample criteria of 104 counts/dL) even when measurements take place four days or more after a rainfall event.



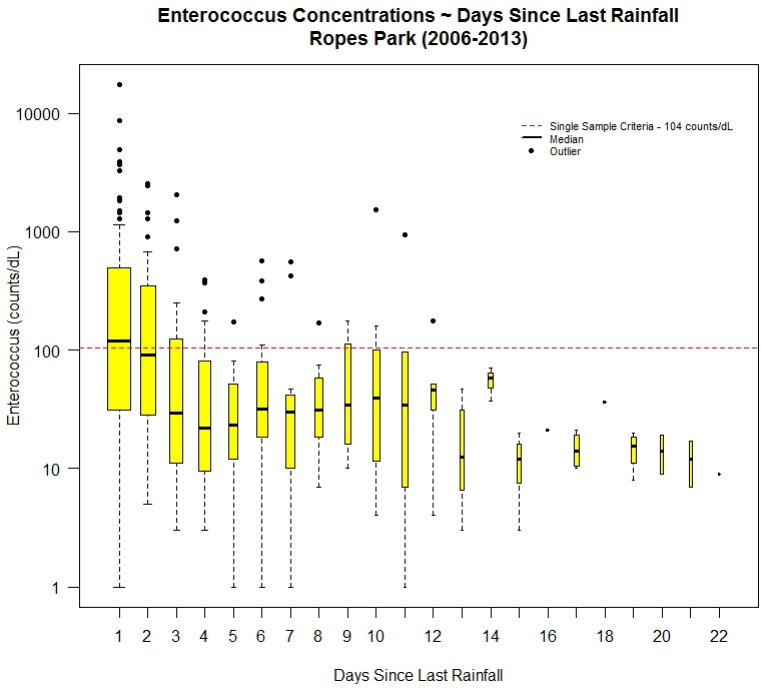


Figure 9. Box and Whisker Plots of Sampling Events at Ropes and Cole Parks.

SECTION 3
PROBLEM IDENTIFICATION & WATER QUALITY TARGETS

3.1 Pollutant of Concern: Characteristics of Bacterial Indicators

The contact recreation use is a common designation for water bodies in the State of Texas, although full support of the contact recreation use is not a guarantee that the water is completely safe from disease-causing organisms. The evolution of the contact recreation criteria currently used by Texas began with criteria first published in 1968 based on general studies done on lakes in the Midwest and in the state of New York using fecal coliform bacteria as an indicator of the potential presence of fecal contamination (U.S. National Technical Advisory Committee, 1968).

The USEPA-recommended criteria for recreational waters in 1976 included a geometric mean criterion of no more than 200 counts/dL, based on five samples collected over a 30-day period and an instantaneous criterion of no more than 10 percent of the individual grab samples exceeding 400 counts/dL. Shortly after their recommendation, these criteria were adopted by the State of Texas in its Surface Water Quality Standards (SWQSs). The criteria, and the studies on which they were based, were heavily criticized following an extensive epidemiological study (USEPA, 1986). The USEPA studies that followed found that fecal coliform was not a good predictor of the risk of disease and recommended new tests and criteria. The USEPA recommended new criteria for swimming areas, using *Enterococcus* as the new fecal indicator organism for marine and inland saline waters, and incorporated the notion of varying criteria with varying levels of swimming use.

In 2000, Texas began using *Enterococcus* Sp. as the preferred indicator bacteria for marine waters to determine support for contact recreation use (Texas Commission on Environmental Quality, 2007). The presence of these bacteria in a water body indicates that fecal waste from warm-blooded species may be contaminating it (U.S. National Technical Advisory Committee, 1968). The standard associated with contact recreation use is designed to ensure that water is safe for swimming, wading (by adults and children) or other water sports that involve direct contact with the water, especially activities that involve the possibility of ingesting the water. High concentrations of certain bacteria in surface water indicate there may be an increased risk of becoming ill from engaging in aquatic recreational activities.

3.2 TCEQ Water Quality Standards for Contact Recreation

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

This report focuses on two designated surface water quality segments of Corpus Christi Bay, both within the City of Corpus Christi; both segments are on the Texas 2010 Clean Water Act Section 303(d) list of impaired water bodies because they do not support their designated contact recreation use.

Table 8 summarizes the designated uses and the applicable criteria for bacterial indicators used to assess the contact recreation use of each water body addressed in this report. It also identifies the year each water body was placed on the Texas Clean Water Act Section 303(d) List of impaired waters for nonsupport of the contact recreation use. The TMDLs detailed in this report only address the contact recreation use.

Table 8. Synopsis of Texas Integrated Report for Waterbodies in the study area

Segment ID	Segment Name	Parameter	Designated Use*				Year Impaired
			CR	AL	GU	FC	
2481CB_03	Cole Park	*Enterococcus*	NS	S	S	NA	2010
2481CB_04	Ropes Park	*Enterococcus*	NS	S	S	NA	2010

* *CR: Contact recreation; AL: Aquatic Life; GU: General Use; F: Fish Consumption; NS: Nonsupport; S = Support Problem Identification.*

Pursuant to Section 303(d) of the federal Clean Water Act, states must establish TMDLs for pollutants contributing to violations of their SWQSs. Table 9 identifies the water bodies requiring TMDLs identified in Category 5 in the 2010 Texas Water Quality Inventory and Section 303(d) List (TCEQ, 2010) as well as the SWQM stations used in the evaluation.

Table 9. Water Quality Monitoring Stations Used for 303(d) Listing Decision.

Segment ID	Segment Name	Description	*Monitoring Station IDs	Year
2481CB_03	Cole Park	Corpus Christi Bay along Cole Park Waterfront	NUE033 NUE032 NUE031	2010
2481CB_04	Ropes Park	Corpus Christi Bay along Ropes Park waterfront	NUE029 NUE028 NUE027	2010

* Note that sampling was discontinued at NUE034 after October 2005.

Table 4 previously summarized the ambient water quality data for the TCEQ SWQM stations on each impaired water body. From these data, key inferences can be made regarding the temporal and spatial extent of the contact recreation use impairment. The water quality target for the TMDLs in the study area is to maintain concentrations for the indicator bacteria *Enterococcus* below the single sample criterion of 104

counts/dL (104 CFU/dL). Maintaining the single sample criterion for indicator bacteria is expected to ultimately result in the attainment of the contact recreation use. The TMDLs described in this document are based on the percent reduction goal required to meet the single sample criterion in both impaired water bodies.

The water quality target for each water body incorporates an explicit five percent margin of safety (MOS). For example, as *Enterococcus* is utilized to establish the TMDLs, the water quality target is 98.8 counts/dL, 5 percent lower than the single sample water quality criterion for *Enterococcus* (104 counts/dL).

3.3 Bacteria Sources

Urban non-point source (NPS) pollution is generated from stormwater runoff, which typically contains pollutants such as dissolved and suspended solids, bacteria, metals, oil and grease, nutrients, oxygen-demanding substances, and pesticides, to name a few. Urban runoff produces a higher volume of water than in rural areas for the same amount of rain because a large extent of the area consists of impermeable surfaces like parking lots, roads, and other forms of urbanization. Also, drainage systems cause loads to breach receiving waters faster and in a more concentrated state than with natural drainage. Major urban NPS sources include motor vehicles, yard fertilizers and pesticides, animal wastes, construction, and erosion (Baird et al., 1996).

Cross-correlation is a statistical technique that can be used to determine the strength of possible relationships between two time series of data (Davis, 1986). Cross-correlation generates a coefficient (r) between negative one and one that represents the strength of the relationship and whether the relationship is normal (positive) or inverse (negative). Cross-correlation coefficients were generated for SWQM parameter values (salinity, depth, temperature, DO, pH, conductivity, and turbidity) collected by CCS over the period from 2011 to 2013 in Corpus Christi Bay to discover the strength of their relationship with *Enterococcus* (Figure 10). An analysis of a smaller, subset of the values was made for SWQM stations associated with Cole Park and another with those associated with Ropes Park. A confidence interval of 95% was computed for each correlation coefficient to differentiate significant correlations from random “noise” in the data. In each of the resulting plots (Figures 10, 11, and 12), *Enterococcus* is seen to correlate with itself at a coefficient of one, which is what would be expected if the analysis is conducted correctly.

The results, shown in Figure 10, for all SWQM stations in the general area of Cole and Ropes Parks have a moderate negative correlation with salinity (-0.58), pH (-0.32) and specific conductance (-0.60) and a moderate positive correlation with daily precipitation (0.55). While the parameters DO (-0.10), pH (-0.27), DO saturation (-0.25), temperature (-0.06), depth (-0.10), and days since last rain event (-0.17) have a weaker negative correlation. Turbidity had the weakest correlation coefficient (0.05) which barely exceeds the 95% confidence interval of (0.037).

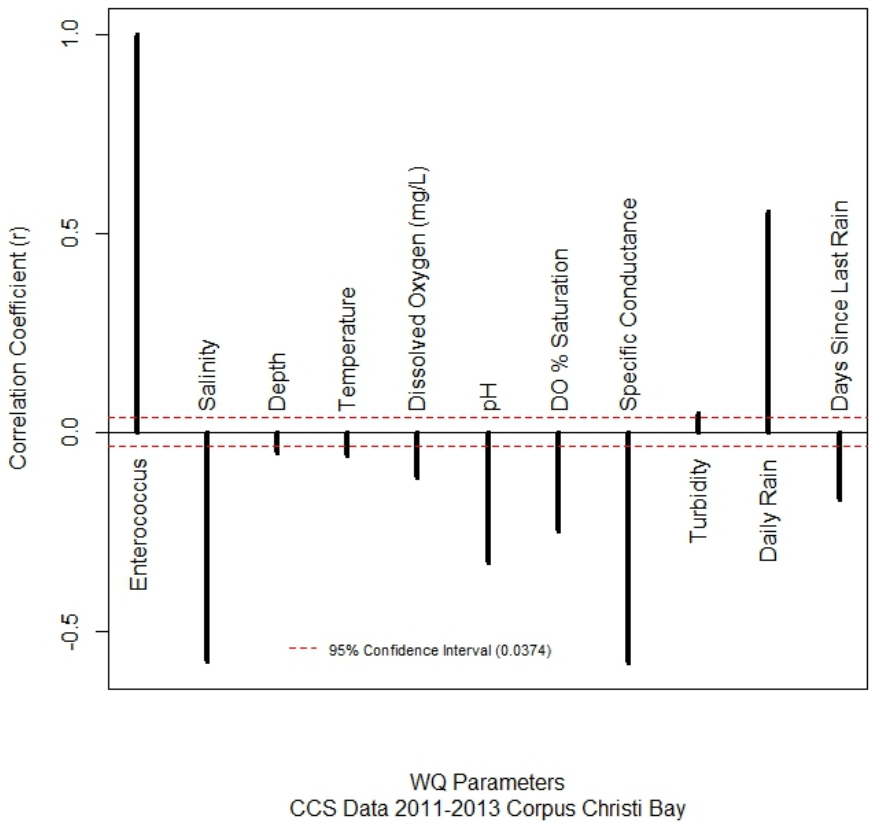


Figure 10. Correlation coefficients of water quality parameters vs. *Enterococcus* in Corpus Christi Bay.

Correlation coefficients shown in Figure 11 reflect the relationship between *Enterococcus* and the water quality data collected at SWQM stations near Cole Park. These data display a moderate negative correlation with salinity (-0.60) and conductivity (-0.60) and moderate positive correlation with daily rainfall (0.56). A weaker correlation is seen with pH (-0.27), DO saturation (-0.25), depth (-0.10), DO concentration (-0.10), temperature (-0.06) and days since last rain (-0.18). Turbidity failed to exceed the 95% confidence interval of 0.059, meaning it is not significantly correlated with *Enterococcus* concentrations. Correlation coefficients for data collected at SWQM stations near Ropes Park are shown in Figure 12. A moderate negative correlation is observed with salinity (-0.60) and specific conductance (-0.59) and a strong positive correlation with daily rainfall (0.75). Weaker correlations exist with pH (-0.29), days since last rain (-0.26), DO saturation (-0.21) and turbidity (0.32). Depth (0.05), along with temperature (-0.01) and DO (-0.05) failed to exceed the 95% confidence interval.

Correlation coefficients generated in the analysis above indicate a strong correlation of *Enterococcus* with precipitation and the concomitant effects of precipitation, like decreased salinity or specific conductance. It can be inferred from this that precipitation events and concomitant runoff are a significant factor in high *Enterococcus* concentrations in Segment 2481CB_03 and Segment 2481CB_04.

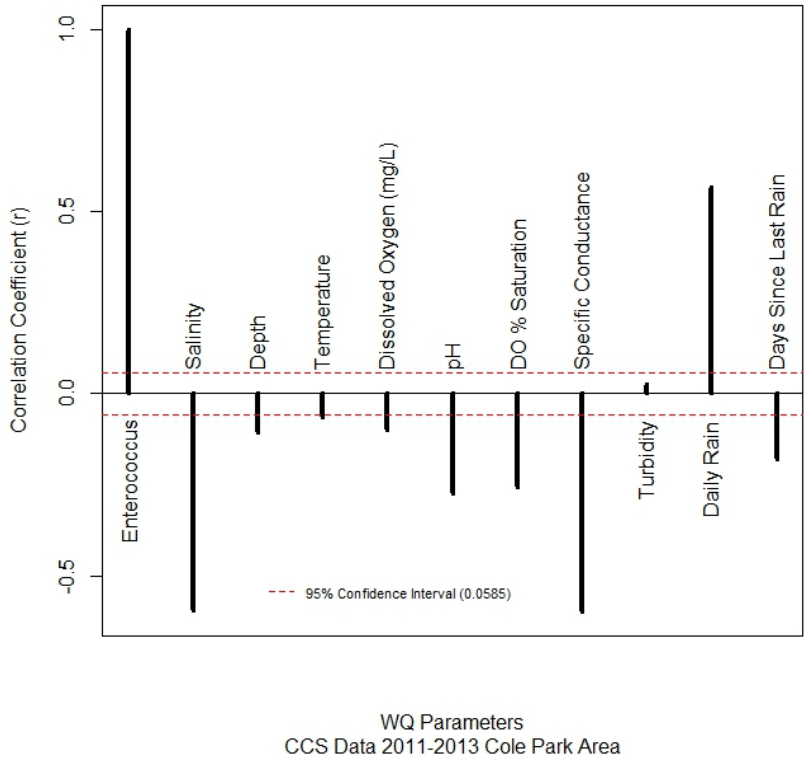


Figure 11. Correlation Coefficients of water quality parameters vs. *Enterococcus* at Cole Park.

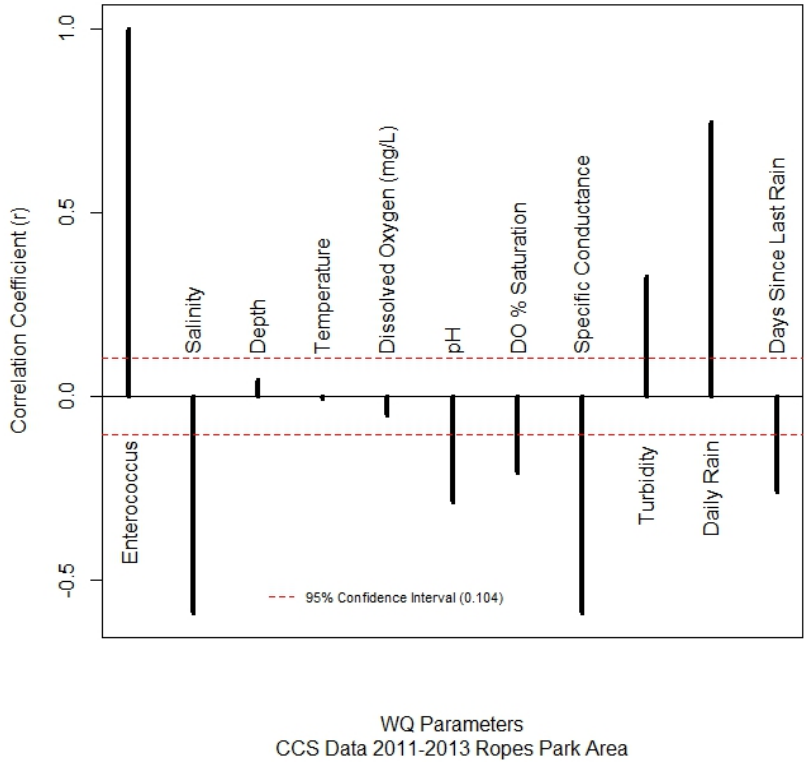


Figure 12. Correlation Coefficients of water quality parameters vs. *Enterococcus* at Ropes Park.

SECTION 4
POLLUTANT SOURCE ASSESSMENT

To support TMDL development, a pollutant source assessment is typically conducted to characterize known and suspected sources of pollutant loading to impaired water bodies. Pollutant sources within a watershed are identified, categorized and quantified according to the information that is available. Fecal bacteria such as *Enterococcus* originate in the intestines of warm-blooded species and the sources of the bacteria may be categorized as point (permitted) or nonpoint (non-permitted) in nature.

Point sources of pollution can be loosely defined as those that enter a water body through a discrete conveyance structure at a single location. Point sources are typically permitted at the federal level through the National Pollution Discharge Elimination System (NPDES) program. Some stormwater runoff may be permitted through NPDES as municipal separate storm sewer systems (MS4).

Non-permitted sources of stormwater runoff that typically cannot be identified as entering a water body through a discrete conveyance at a single location are often referred to as nonpoint sources. For example, non-permitted sources include land activities that contribute bacteria to surface water as a result of unregulated rainfall runoff or failing on-site sewage system facilities (OSSFs). For the TMDLs in this report, all sources of pollutant loading not regulated by a NPDES or TPDES permit are considered nonpoint sources. The following discussion describes what is known regarding permitted and non-permitted sources of bacteria in the watersheds discharging to Corpus Christi Bay in the areas of Cole and Ropes Parks.

4.1 Point Sources: NPDES/TPDES-Permitted Sources

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

- TPDES municipal wastewater treatment facilities (WWTFs);
- TPDES industrial WWTFs;
- TPDES municipal no-discharge WWTFs;
- TPDES regulated stormwater (e.g., MS4s); and
- TPDES Concentrated Animal Feeding Operations (CAFOs).

Continuous point source discharges such as WWTFs, could result in discharge of elevated concentrations of fecal bacteria if the disinfection unit is not properly maintained, is of poor design, or if flow rates exceed the facility's disinfection capacity.

While no-discharge facilities do not discharge wastewater directly to surface water bodies, it is possible that collection systems associated with these types of facilities may be a source of bacteria loading to surface waters. Also, as with WWTFs that discharge directly to surface water bodies, the retention capacity of some no-discharge facilities may become overwhelmed by high rainfall runoff volumes, causing unauthorized discharges of pollutants to surface water bodies.

Permitted stormwater runoff from TPDES-regulated discharge areas, called municipal separate storm sewer systems (MS4), can also contain high fecal bacteria concentrations if the systems lack adequate stormwater infrastructure or management practices.

CAFOs are recognized by USEPA as significant sources of pollution, and may have the potential to cause serious impacts to water quality if not properly managed.

All of the study area associated with the TMDLs described in this document is regulated under the TPDES stormwater discharge permit held by City of Corpus Christi. There are no NPDES or TPDES-permitted WWTFs, no-discharge WWTFs or CAFOs that discharge within the study area. Additionally, the study area has been serviced by a municipal sanitary sewer collection system since the 1940's.

4.2 Permitted Sources: NPDES/TPDES Regulated Stormwater

In 1990, the USEPA developed rules establishing Phase I of the NPDES Stormwater Program (40 CFR Parts 122, 123 and 124). These rules were designed to prevent harmful urban nonpoint source pollutants from being discharged into water bodies.

Phase I of the program required medium and large permitted dischargers (those generally serving populations of 100,000 or greater) to implement a stormwater management program as a means to control polluted discharges. Approved stormwater management programs for medium and large permitted discharges are required to address a variety of water quality-related pollutant sources, including roadway runoff, municipal-owned operations, and hazardous waste management.

On September 14, 1998, the state of Texas assumed the authority to administer the NPDES program in Texas. The TCEQ's TPDES program now has federal regulatory authority to regulate discharges of pollutants to Texas surface waters. When evaluating pollutant loads originating from stormwater runoff, a critical distinction must be made between stormwater originating from an area under an NPDES/TPDES regulated discharge permit and stormwater originating from areas not under an NPDES/TPDES regulated discharge permit.

To characterize pollutant loads from stormwater runoff, it is necessary to segregate stormwater into two categories: 1) permitted stormwater, which is stormwater originating from an area covered by an NPDES/TPDES stormwater permit; and 2) non-permitted stormwater, which is stormwater originating from any area not covered by an NPDES/TPDES stormwater permit. Each sub-watershed in the study

area is within the area covered under the City of Corpus Christi's MS4 permit (NPDES No. TXS00601; TPDES Permit No. WQ0004200000). The jurisdictional boundary of the Corpus Christi MS4 permit is dictated by the corporate boundary of the City of Corpus Christi.

Under the City of Corpus Christi's MS4 permit, the City of Corpus Christi, Del Mar College District, Port of Corpus Christi Authority, Texas A&M University-Corpus Christi, and Texas Department of Transportation are designated as co-permittees. Table 10 lists the total area and percentage of area within each sub-watershed of the City of Corpus Christi MS4 permit.

Table 10. Percentage of Permitted Stormwater in each Watershed.

Sub-Watershed #	Basin Reference	Acres/ Hectares	% of Watershed Included in Permit
103	Brawner PKWY	1932/782	100
104	Ropes/Carroll	7/3	100
105	Oleander Ave, and Point	22/9	100
200	Hewitt Estates, First Baptist Church	123.5/50	100
220	Louisiana St	2041/826	100
230	Ayers St, Christus Spohn	91/37	100
170	Sinclair St	30/12	100
180	Rossiter St	104/42	100
190	Airheart Point/ Ocean Way	32/13	100

4.2.1 Corpus Christi MS4 Permit Summary

The Corpus Christi MS4 Permit (NPDES No. TXS00601; TPDES Permit No. WQ0004200000) is authorized by the Texas Commission of Environmental Quality (TCEQ) and USEPA and permits the City of Corpus Christi, Del Mar College District, the Port of Corpus Christi Authority, the Texas Department of Transportation, and Texas A&M University – Corpus Christi to discharge from the municipal separate storm sewer system (MS4) so long as private property rights are respected. This permit was issued on August 11, 2008.

The requirements of the Corpus Christi MS4 include the reporting of discharge characteristics for, but not limited to, the 25 characteristics listed in the MS4 permit including composite samples of total nitrogen and total dissolved solids and instantaneous grab samples of temperature and *E. coli*. All samples are to be taken, at a minimum, two times per season to develop a daily maximum. There are no specified limits currently set for the discharge characteristics. The current stormwater sampling station for Corpus Christi Bay is at Outfall 001 ("Carmel – Gollihar"), located between Staples St. and Fort Worth St. along the Carmel Parkway ditch.

4.3 Permitted Sources: NPDES No-Discharge Facilities and Confined Animal Feeding Operations (CAFOs)

There are no No-Discharge Facilities or CAFOs located within the study area.

4.4 Non-permitted Sources: Unregulated Stormwater, Failing On-site Sewage Facilities (OSSFs) and Direct Deposition

Non-permitted sources (i.e., nonpoint sources) include sources associated with non-regulated activities or from illicit conditions. Typically, these sources include pollutants that cannot be identified as entering the water body at a specific location.

Water quality data collected from streams draining urban communities often show concentrations of fecal bacteria at levels greater than the host state's instantaneous standards. Data from the USEPA's National Urban Runoff Project indicate that the average fecal coliform concentration from 14 watersheds in different areas within the United States was approximately 15,000 counts/dL in stormwater runoff (USEPA, 1983). Although the exact breakdown of the sources contributing fecal bacteria to urban stormwater is nearly impossible to discern with any degree of certainty, studies have shown that non-permitted stormwater can be a significant source of fecal bacteria in urban runoff. Non-permitted sources of bacteria can emanate from wildlife, agricultural activities, livestock/domesticated animals, improperly constructed land application fields, failing on-site sewage facilities (OSSF), faulty wastewater conveyance systems, domestic pets and unregulated urban runoff in general.

Failing on-site sewage treatment facilities (OSSFs) can be an important non-permitted source of fecal bacteria in some urban and suburban communities. However, as previously mentioned, the portion of Corpus Christi encompassed by the TMDL study area has been serviced by a municipal sanitary sewer collection system since the 1940's. There are no known OSSFs in the TMDL study area.

Sometimes bacteria loads can emanate from in-situ sources or sources in very close proximity to a receiving water body. This process is commonly referred to as direct deposition. In the case of fecal bacteria, direct deposition usually means defecation directly into the receiving water body or activities or processes that result in the direct contribution of fecal matter to the receiving water body. Potential sources of direct deposition to the impaired segments include human recreational activities (e.g., pre-potty-trained bathers or high densities of recreationists of any age), domestic pets and wildlife (particularly avian species).

As discussed in Section 2 (Summary of Existing Data), analysis of existing meteorological and water quality data shows that, although most exceedances of the contact recreation criteria in the impaired segments occur during or immediately after rainfall events, a notable number of exceedances have occurred during dry weather

conditions. One of the potential sources of these exceedances could be direct deposition.

4.5 Sanitary Sewer Overflows (SSOs)

Sanitary sewer overflows (SSOs) are permit violations that must be addressed by the responsible TPDES permittee. SSOs are most often the result of blockages in the sewer collection pipes and are caused by tree roots, grease and other debris that block conveyance. The TCEQ maintains a database of SSO data collected from wastewater operators in the study area. Table 11 shows the occurrences and volume of SSOs within the study area from 2008 to 2013. Figure 13 shows the location and magnitude of the SSOs documented in the study area.

Table 11. Sanitary Sewer Overflow (SSO) Summary for the study area.

Year	No. of Occurrences	Amount (Gallons)				
		Min	Max	Median	Mean	Sum
2008	387	0	3000	16	57.28	22168
2009	368	0	2000	15	32.10	11813
2010	321	1	41276	20	170.00	54456
2011	213	2	180	20	24.83	5235
2012	248	1	300	10	20.15	4977
2013	103	1	300	20	28.48	2933

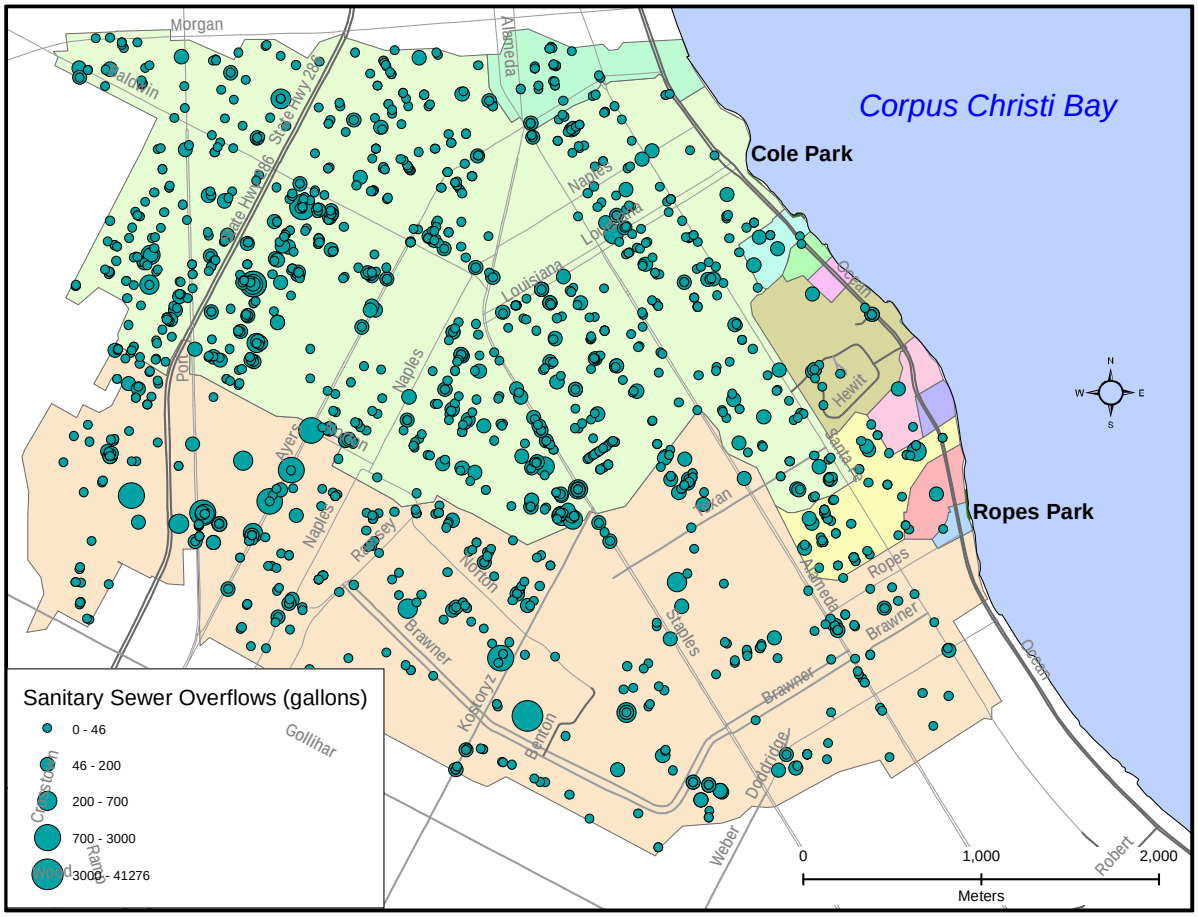


Figure 13. Sanitary Sewer Overflow Locations (2008-2013).

4.6 Wildlife and Unmanaged Animal Contributions

In developing bacteria TMDLs, it is important to identify the potential for bacteria contributions from wildlife and unmanaged animals in the watershed of the receiving water bodies. Fecal bacteria from wildlife and unmanaged animals are deposited onto riparian land surfaces or shorelines, where they may be washed into nearby water bodies by rainfall runoff. Consequently, bacteria contributions from wildlife and unmanaged animals can be an important source of bacteria loading to a water body even in urban settings.

Typically, in coastal watersheds, there is a significant population of avian species that frequent riparian corridors and coastal shorelines. However, currently there are insufficient data available to accurately estimate the populations and spatial distributions of avian species within the TMDL study area. The number and distribution of unmanaged animals in the TMDL watersheds is also not well documented. Consequently, it is difficult to assess the magnitude of fecal bacteria contributions to the TMDL watersheds from wildlife and unmanaged animals as general categories.

4.7 Non-Permitted Agricultural Activities and Domesticated Animals

There are a number of non-permitted agricultural activities that can also be sources of fecal bacteria loading. Given the fact that the study area is highly urbanized, livestock and other domesticated animals are not found in high quantities in these sub-watersheds and, therefore, these sources are not considered significant contributors of bacteria loading to the impaired segments.

4.8 Domestic Pets

Fecal matter from dogs and cats can be transported to streams by runoff from urban and suburban areas and is a potential source of bacteria loading to Corpus Christi Bay. On average, nationally, there are 0.58 dogs per household and 0.66 cats per household (American Veterinary Medical Association, 2002). Using the U.S. Census data at the block level (U.S. Census Bureau, 2010), dog and cat populations can be estimated for the target sub-watersheds. Table 12 summarizes the estimated number of dogs and cats in the TMDL study area.

Table 12. Estimated Numbers of Pets in the TMDL Sub-watersheds.

Dogs	Cats
9052	10301

Table 13 provides an estimate of the *Enterococcus* loading from pets to the impaired segments. These estimates are based on average *Enterococcus* per dog defecation "event" of 5.43 x 10^6 counts. It is assumed that, on average, an animal will have one "event" per day, and that, for cats, the load will be one order of magnitude less per event, based on fecal coliform numbers as described by previous studies (Cox, 2005; Schueler, 2000). Only a small portion of these loads is expected to reach the receiving water bodies, through wash-off of land surfaces and conveyance in a runoff event.

Table 13. Estimated Fecal Coliform Daily Production by Pets in the TMDL Sub-watersheds.

	Dogs	Cats
Fecal Coliform	2.81 x 10^{11}	2.37 x 10^{10}
E. coli	1.77 x 10^{11}	1.49 x 10^{10}
Enterococcus	4.91 x 10^{10}	4.15 x 10^{9}

4.9 Bacteria Re-growth and Die-off

Certain enteric bacteria can regrow in organic materials if appropriate conditions prevail (e.g., warm temperature, sufficient moisture, etc.). It has been shown in the scientific literature that fecal bacteria in improperly treated effluent can regrow during their transport in pipe networks and that these organisms can also regrow in organic-rich materials such as compost and sludge (Alkan et al., 1995). While the die-off of indicator bacteria has also been demonstrated in natural water systems due to the presence of sunlight and predators, the potential for their regrowth is less well understood (Boehm et al., 2005; Kay et al., 2005; Medema et al., 1997; Sinton et al.,

2002) . Both processes (regrowth and die-off) are in-stream processes. Although regrowth is not explicitly represented in the bacteria source loading estimates for the receiving water bodies included in the TMDL described in this report, bacteria die-off rates are included as part of the TMDL modeling.

SECTION 5
TECHNICAL APPROACH AND METHODS

The objective of a TMDL is to estimate the maximum allowable pollutant loads to a receiving water body and to allocate these loads to specific categories of pollutant sources in the watersheds associated with the receiving water bodies, so that appropriate control actions and management measures can be implemented to limit pollutant contributions to the allocations and maximum loading limits estimated as part of the TMDL analysis. A TMDL is expressed as the sum of three elements, as described in the following mathematical equation:

Equation 1. Total Maximum Daily Load Formula

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

where:

TMDL = Total Maximum Daily Load
Σ WLA= Sum of Wasteload Allocations
Σ LA= Sum of the Load Allocations and
MOS = margin of safety

The waste load allocation (WLA) is the portion of the TMDL allocated to existing and future permitted (point) sources, including MS4-regulated stormwater discharges. The load allocation (LA) is the portion of the TMDL allocated to non-permitted (nonpoint) sources, including natural background sources. The Margin of Safety (MOS) is a portion of the TMDL reserved to account for any uncertainty in the TMDL analysis; it is intended to ensure that the standard for contact recreation will be met. Therefore, the sum of the TMDL allocations to made to point and nonpoint sources can then be defined as the TMDL minus the MOS.

40 CFR,Part 130.2(1), states that TMDLs can be expressed in terms of mass per time, toxicity, or other appropriate measures. For *Enterococcus* bacteria, TMDLs can be expressed as counts (CFUs) per day or as percent reduction goals for the pollutant loading causing the impairments. A TMDL is supposed to represents the maximum daily pollutant load a water body can assimilate while still attaining its designated uses. However, given that the pollutant loadings associated with Segments 2481CB_03 (Cole Park) and 2481CB_04 (Ropes Park) occur mainly during rainfall events, estimating TMDLs for these segments is a difficult technical challenge. The analysis presented in this document estimates both allowable pollutant loads and the percent reduction goals needed to achieve WQ standards for contact recreation in the impaired segments using a calibrated numerical model to simulate pollutant loadings over variety of weather conditions (e.g., dry years, wet years).

5.1 Using Numerical Models to Develop TMDLs

Water quality at any discrete point within a watershed is the result of all processes that have occurred upstream of that particular point. Major watershed processes include the accumulation of pollutants on land surfaces (pollutant buildup), conversion of

precipitation to runoff (overland and channelized flow), and removal of constituents on surfaces in contact with the water (wash off). Other processes may include dilution and decay (i.e., dye-off, predation by other organisms, or inactivation through adhesion to colloidal particles).

Models can be used to aid in the understanding of physical systems. A model is any mechanism that can simulate a process or system (Anderson and Woessner, 1992). Models can be laboratory scale devices constructed using actual materials and involving the same physical forces as found in nature, like a flume to model surface water flow (McDaniel et al., 2013) or a sand tank to model ground water movement (Anderson and Woessner, 1992). Many times it is impractical to build a physical model, so numerical models may be created instead.

Numerical models often simulate natural systems using mathematical formulas (governing equations) or statistical relationships that represent the physical, chemical and biochemical processes at work in the systems they simulate. Numerical models can be divided into two groups based on the methods used to represent the physical systems they simulate. Stochastic models use statistical probability to define the physical processes in the system. Deterministic (physical or process-based) models use governing equations to represent the physical processes involved in the actual system being modeled. Deterministic models do not contain the random elements that are inherent in probability-based models.

A numerical model can be used to produce continuous simulated flow and water quality data that can be used to forecast these parameters under future conditions or to fill gaps in observed field data. Model simulations can also be used to calculate loadings of modeled constituents at any discrete location and/or time within the model domain.

Numerical models have been applied to the Corpus Christi Bay area in the past. Quenzer (Quenzer et al., 1998) developed a GIS-based numerical model to assess non-point source loadings (primarily nutrients) to the Corpus Christi Bay system. A similar model was used in the Galveston Bay area (Zoun, 2003) to assess bacteria loading. A Bacteria TMDL project conducted on Oso Creek and Oso Bay (Hay and Mott, 2005, 2006) also applied a GIS-based model to assess bacteria loadings to those water bodies and to simulate the results of load reduction plans.

5.2 Development of the Numerical Model

5.2.1 Conceptual Model

The modeling approach used for these TMDLs is based on geographic information system-based (GIS-based) datasets and dataset derivatives as model inputs. The conceptual model of the TMDL modeling system is as follows:

1. Fecal bacteria from warm-blooded animals accumulate over time on surfaces exposed to the atmosphere. The quantity of accumulated fecal matter is a function of land cover and use. The accumulated fecal matter is always present.

2. A precipitation event with sufficient magnitude can generate overland flow of water that carries some of the fecal bacteria down slope until it becomes channelized flow.
3. Channelized flow containing the fecal bacteria enters the drainage channels and stormwater conduits and flows towards the bay.
4. During the channelized flow process fecal bacteria begin to die or inactivate due to various forces such as predation or inhospitable environments.
5. Flow is accumulated in the stormwater system, routed through channels and conduits and discharged to Corpus Christi Bay at or near the impaired segments, where mixing with bay water occurs.

The primary forcing in this modeled system is assumed to be runoff from precipitation. Some studies (Hay and Mott 2006; Stein and Ackerman 2007; Mott, Hay et al. 2009) have noted that dry weather loading can be a significant contributor to poor water quality and some of the data collected by CCS in the study area corroborates this observation. However, this type of loading is not driven by runoff events. Dry weather loads can be incorporated into a runoff-based model as a constant flux, provided there is enough data collected during dry weather to indicate its presence and to determine the flux rate. This is the case for the TMDL model presented in this document.

The model in this report was developed under a Quality Assurance Project Plan (QAPP) titled *"Modeling for TMDL Investigation for Bacteria in Corpus Christi Bay Beaches Quality Assurance Project Plan"* with an effective start date of July 17, 2013.

5.2.2 Modeling Process and Design

The major processes identified in the conceptual model are the accumulation of fecal bacteria on various surfaces, conversion of precipitation to runoff, routing of runoff to channelized flow, the decay of bacteria during channelized flow and the mixing of the discharged runoff with the bay water at the segments of interest. Each of these processes can be defined using a mathematical relationship (governing equation) that can use real field measurements as input variables to the calculations. The results of the calculations can then be used as inputs for subsequent processes. For the purposes of the discussion that follows, the model is divided into two simultaneous processes: the hydrologic component, which drives the movement of water through the system; and the physico-biological component which describes the accumulation and decay of the fecal bacteria.

The hydrologic component of the model is governed by the hydrologic equation (law of mass conservation):

Equation 2. The Hydrologic Equation

Inflow = outflow +/- change in storage

where:

Inflow = precipitation within the model boundaries,

Outflow = discharge to the impaired segments minus infiltration to the soil

Storage = precipitation intercepted by vegetation or buildings or depression storage

Model boundaries are defined by the limits of the contributing basins (i.e., sub-watersheds) of the stormwater collection systems that discharge closest (or are most likely to affect) the impaired segments (see Figure 2). Within the boundaries of the model, runoff is calculated based on the Rational Equation:

Equation 3. The Rational Equation (Fetter 2001)

$$Q = C \times I \times A$$

where:

Q= peak runoff rate
C=runoff coefficient
I=rainfall intensity
A=area

The peak runoff rate calculated in the Rational Equation (Equation 3) is the volume of water that is expected to become runoff over the unit of time defined by the rainfall intensity. Peak runoff, as used in this modeling effort, represents the total runoff generated during the interval of the rainfall intensity. Runoff is accumulated over the basin (sub-watershed) and routed to the stormwater collection system, calculated by grid multiplication, with the mean of range runoff coefficient (C) as described in Table 14.

Table 14. Land Use code and associated American Society of Civil Engineers (ASCE) runoff coefficients for grid incorporation

City of Corpus Christi Land Use Code	ASCE Area Description	C Range (Fetter, 2001)	C Mean (calculated from Range)
AG,CP,PARK	Parks, Cemeteries	.10-.25	0.175
ROW, VAC, vac	Unimproved	.10-.30	0.20
PO,COM	Downtown (business)	.70-.95	0.825
LI	Light Industrial	.50-.80	0.65
HI	Heavy Industrial	.60-.90	0.75
MDR	Detached Multi units	.40-.60	0.50
HDR	Attached Multi units	.60-.75	0.675
ER	Residential Suburban	.25-.40	0.325
LDR	Single-family	.30-.50	0.40
PSP	Neighborhood (business)	.50-.70	0.60
TRANS	Asphalt and Concrete	.70-.95	0.825

Once runoff has been accumulated and enters channelized flow (for discharge and water quality determinations), each subsection of the drainage system is treated as a constantly stirred reactor tank (Aris, 1999; Denbigh and Turner, 1971).

Following the law of mass conservation (Equation 2), the channelized flow is routed along the stormwater collection system using Manning's Equation and the dimensions and altitude gradients of the stormwater conveyance channels to determine the flow velocity of runoff discharging to the bay (Equation 4).

Equation 4. The Manning Equation (Fetter 2001)

$$V = \frac{1.49 R^{\frac{2}{3}} S^{\frac{1}{2}}}{\mathrm{n}}$$

where:

V=velocity
R=hydraulic Radius
S=gradient
n=Manning roughness coefficient

The water quality component of the model tracks the bacteria as it moves through the system, driven by the forcing of the hydrologic component of the model. Accumulation of fecal bacteria in the runoff is based on (1) land cover/land use that has been described by the City of Corpus Christi, (2) event mean concentrations (EMCs) which describe the total constituent mass washed off of the land surface divided by the total runoff volume for a particular land use over a rainfall event (United States Environmental Protection Agency, 1983) and (3) event concentrations (ECs) which describe the concentration of bacteria (*Enterococcus*), that is continuously available for transport in runoff (Hay and Mott, 2006). ECs can be viewed as EMCs adjusted to site-specific conditions.

While EMC values represent the average concentration of a contaminant in runoff from a particular type of land use over a runoff event, they inherently contain decay and dilution factors that occur over the duration of the event. For this reason, they are not particularly well suited for modeling runoff at shorter time intervals than the runoff event itself.

In another TMDL study on a neighboring watershed (Oso Creek) a method was implemented that produced values for contaminant availability that could be used to modify literature-based EMC values. This method captured the entrainment process of the pollutant while the precipitation portion of the runoff event proceeded (Hay and Mott, 2006). The adjusted values were described as event concentrations (ECs).

EC values were conceptualized and developed when it was noted that a simulation, iterating at 2 hour intervals, produced in-stream concentrations of *Enterococcus* consistently lower than the measured values at the same time and location. To develop the ECs the researchers chose a SWQM station that measured discharge and water

quality from a small sub-watershed of Oso Creek (completely within the City of Corpus Christi) that contained all land use types from the main Oso Creek watershed. Initial loads (concentrations divided by flow) were estimated by back calculation from field WQ measurements at the sub-watershed outfall and then by solving for initial load in Equation 5 for several runoff events. This value was then distributed proportionally to each land use based on the area represented in the sub-watershed and the ratio of magnitudes between land use types from Baird et al. (1996).

Equation 5 Calculation of Event Mean Concentration (Lee, 2002)

$$EMC_T = \frac{\sum[C_t Q_t \Delta t]}{\sum[Q_t \Delta t]}$$

where:

EMC_T=Total enterococci EMC of runoff
C_t=time variable concentration (CFU 100ml^{-1})
Q_t=time variable flow (m^3 day^{-1})
Δt=discrete time interval

Once the bacteria are entrained in the runoff and enter channelized flow they are subject to decay. Decay is the loss of bacteria due to die-off, settling, predation, inactivation due to adhesion, or exposure to inhospitable environments (such as low temperatures, high salinity or bright sunlight). Values for bacteria decay in surface water can be found in the scientific literature (Alkan et al., 1995; Boehm et al., 2005; Medema et al., 1997; Noble et al., 2004). Decay rates vary for fresh water and salt water. Bacteria decay rate is calculated using Equation 6.

Equation 6. First order decay rate for bacteria (Crysup, 2002)

$$K_B = K_{B1} + K_{BL} + K_{BS} K_a$$

where:

K_{B1}=death rate as a function of temperature, salinity, and predation
K_{BL}=death rate due to exposure to sunlight
K_{BS}=net loss due to settling
K_a=after growth rate

During transport, the bacteria load is decayed based on the period of time it spends in a particular segment using Equation 7.

Equation 7. Decayed bacteria load

$$L = L_0 e^{-K_B t}$$

where:

L=decayed load

L_O=initial load from watershed
K_B=overall first order decay rate
t=travel time

Since decay is so closely coupled with time in channelized flow it is beneficial to break the contributing area up into small sub-basins (sub-watersheds) to provide a more detailed tracking of bacteria loads and a more representative time for calculating decay. Sub-basins (sub-watersheds) are well defined in the City of Corpus Christi Stormwater Master Plan (Green and West, 2009) and the City of Corpus Christi Infrastructure Mapbook (City of Corpus Christi, 2006) documentation.

Other non-runoff processes may exist in the contributing area that can generate additional bacteria loadings to the system. These processes are generally characterized as dry weather loading and can contribute significantly to the total pollutant load. Dry weather loading can emanate from sewage spills and overflows (SSOs), broken/leaking sewer lines and from direct deposition of fecal matter into the water body. Records of sewage spills and overflows are kept by the City of Corpus Christi and reported to the TCEQ. A flux from dry weather events can be determined if sufficient data is available. This type of loading can be represented in the model as a constant flux.

5.2.3 Data Preparation and Processing

The GIS software ArcGIS was used to prepare spatial datasets as model inputs. Spatial datasets include precipitation grids, EC grids and sub-watershed grids/polygons. The spatial dataset were then converted to time series text files that were processed using the open-source mathematical modeling software R (R Development Core Team, 2005).

Governing equations cited in Section 5.2.2 of this document were coded into R following the conceptual model process described in Section 5.2.1. The model can run on various time steps depending on the temporal resolution of the input data. Previous models have run at a 2-hour temporal resolution. This frequency of iteration requires a different approach to EMC values as described in Section 5.2.2 and uses the event concentration values described in Table 15. A concurrent water quality monitoring effort collected bacteria (*Enterococcus*) concentrations at stormwater outfalls at nominal intervals through runoff events. These data were used for model calibration.

Calculation of bacteria (*Enterococcus*) load from a sub-watershed was done at a nominal temporal frequency (e.g. 1 hour intervals) by multiplying the hourly values from the precipitation grid by the runoff coefficients and ECs in the land use grids (Equations 8 and 9).

Table 15. Event Concentration values (counts/dL) as applied in gridded dataset for initial loading calculations.

Type	City of Corpus Christi Classification	Revised EMC Oso Creek (Hay and Mott, 2006)	EMC (Baird et al., 1996)	EC from Oso Creek (Hay and Mott, 2006)
Residential	LDR, MDR, HDR, ER	41320	20000	305316
Commercial	COM, PO, PSP	14246	6900	105264
Industrial	LI, HI	20027	9700	147981
Transportation	TRANS	109427	53000	808562
Crop/ Range Land	AG,VAC, PARK, CP	8500	0/37	62807
Not Classified	DC, WATER	8500	0	62807

Equation 8. Computation of runoff volume using ArcGIS

$$\text{Runoff volume} = \text{precipitation grid} * C$$

Equation 9. Computation of Load using ArcGIS

$$\text{Load} = \text{Runoff volume} * \text{EC grid}$$

Loading for each sub-watershed is calculated using the zonal statistics tool in ArcInfo (Environmental Systems Research Institute, 2013). These loadings are calculated for each time step of the simulation and then exported to the mathematical modeling software R as a text file.

With the initial loadings, R performs the hydrologic functions of routing the flow volume from each sub-watershed to the main conduit(s) at a prescribed time step using Manning's Equation (with conduit dimension and slope) to calculate flow and current velocity and, hence residence time. The model simultaneously moves the bacteria load through the conduits using the residence time for each sub-watershed conduit to decay the load using a specified decay constant. The model produces an hourly runoff volume and bacteria load at each outfall of each modeled stormwater basin (sub-watershed) to Corpus Christi Bay.

5.3 Estimating Loading and Simulations

The TMDL model described in the previous sections was used to calculate discharge volume and bacteria (*Enterococcus*) load (and concentrations) at major stormwater outfalls in the vicinity of Ropes and Cole Park (Segments 2481 CB_04 and 2481 CB_03). The intended use of this information is to calculate total loading to the Corpus Christi Bay beaches near these outfalls.

The calibrated model can be used to simulate conditions under different climate conditions (wet year vs. dry year) or various load reduction plans. Desired load reductions can be simulated by evaluating each land use or land-cover EC to see which

contribute the most loading to the system, and by systematically reducing ECs from the most significant sources (land uses) until a loading is achieved that results in an end concentration that meets the contact recreation criteria in the receiving water bodies.

5.3.1 Initial simulations

During the initial simulations, several factors became apparent that would limit the ability of the model to produce reliable output. These factors initiated a review of the conceptual model and the model code. Primary calibration of the model was performed on the hydrologic component of the model using the Brawner Parkway discharge. This stormwater basin was selected for primary calibration because of the small IQR of values seen in the WQ measurements taken at and near Ropes Park and because it represents a large portion of the study area (Figure 2, Table 11).

During the calibration process, and also during field data collection activities, it was noted that the hydrologic system (stormwater sewer) responded rapidly to precipitation events and quickly emptied the event generated runoff into the Corpus Christi Bay. During large events, the simulated volume of runoff overloaded the models ability to move fluid through the system. Precipitation depths, which drive the runoff portion of the model are not available in time intervals shorter than one hour for this particular data set. So, to prevent the model from overloading during large runoff events, the model code was modified to subdivide each hourly time step into four sub-steps by dividing the runoff and bacteria load input by four and processing them at this shorter input time step (moving the water and bacteria down gradient and simultaneously decaying the bacteria load) four times per hourly model time step.

A secondary calibration was performed on the bacteria component of the model. During this process, it was observed that some mixing between the runoff in the conduit and the bay water occurred upstream of the SWQM stations used for calibration of the model, because the outfalls are partially submerged box culverts that open directly into the bay and, during periods of no runoff, bay water intrudes a significant distance into the stormwater culverts. This situation was evident at the two major outfalls (Brawner Parkway and Louisiana Avenue) which together account for 90% of the drainage from the study area. This situation required a mixing factor to be applied to the model code to account for the mixing of stormwater with the bay water prior to its arrival at the confluence with the bay, where bacteria concentrations were measured.

Challenges in collecting water quality measurements and discharge data for model calibration resulted in only a few usable calibration targets over two runoff events. The primary challenge was the swiftness of flow through the system and the mobilization time needed to capture discharge and water quality measurements. This also imposes a limited ability to match model output (concentration and discharge) with measured data to calculate model error.

5.3.2 Model modification and calibration

In order to address the issues described in Section 5.3.1 there were several modifications made to the model to improve its performance in predicting discharge and bacteria loading.

5.3.2.1 Modifications

The first modification made to the TMDL was discussed in Section 5.3.1. Hourly input data (runoff and bacteria load) generated by the GIS software was split into four. This provided a means to keep runoff and bacteria load moving through the system at a faster rate without overwhelming the model code with large runoff volumes during a particularly strong precipitation event.

The second modification made to the TMDL model was also briefly discussed in Section 5.3.1. Plans for conducting deterministic and stochastic in-beach fate and transport modeling were abandoned. That is, process-based modeling of bacteria in the bay segments and multivariate linear regression methods for relating bacteria concentrations measured at the stormwater outfalls to bacteria concentrations measured at compliance points were eliminated from the model and, instead, a constant mixing factor was introduced as a simplified replacement. This simplified approach led to a modification in the conceptual model which posited that the modeled concentrations at the discharge points were similar enough to those measured at the compliance points (TGLO SWQM stations) that the load reductions evaluated by assessing the change in the bacteria concentrations modeled at the discharge points (i.e., stormwater outfalls) could be used to assess compliance at the SWQM stations. This is a reasonable, albeit slightly conservative, approach as during high volume storm events, flow from the Brawner and Louisiana culverts pushes stormwater several hundred feet in several directions into the bay and the beaches in Cole and Ropes Parks are located adjacent to these, and several other, stormwater outfalls.

5.3.2.2 Calibration

The TMDL model was calibrated using discharge and bacteria concentration measurements collect by CCS and Center for Water Supply Studies (CWSS) under a QAPP titled *"TMDL Investigation for Bacteria in Corpus Christi Bay Beaches Quality Assurance Project Plan"* with an effective date of February 4, 2013. The calibration data was collected over two precipitation events, one occurring on June 30, 2013 and the other occurring on July 17, 2013.

Primary calibration (discharge) and secondary calibration (bacteria concentration) were applied to the Brawner Parkway outfall first for the two runoff events where field measured calibration points were available. Calibration was achieved by adjusting initial inputs (runoff and bacteria load) either up or down until the model output agreed with on-site measurements (calibration points) within a reasonable error. Runoff input, which used a mean C for each land use type (Table 14) produced higher than measured discharge volumes and was gradually reduced until the modeled discharge approximated the measured discharge. Final calibration of discharge on average required only 33.3% of the runoff volume calculated by GIS using the ASCE C

value. The bacteria loading was adjusted in two parts. The first adjustment to the bacteria loading involved a 25% reduction in the input bacteria load calculated by the GIS analysis to reduce the outfall concentrations to within an order of magnitude of the measured values. The second part of the calibration adjusted to the concentration measured at the outfall using the conduit bay water mixing factor.

Once the calibration process was complete on the Brawner Parkway and Ropes Park outfalls, the same values were tested on all other basins. This allowed the modeler to evaluate the calibration adjustments assessing how well they represented the overall basin and it limited the effects of over fitting which provides good results but only over the calibration period.

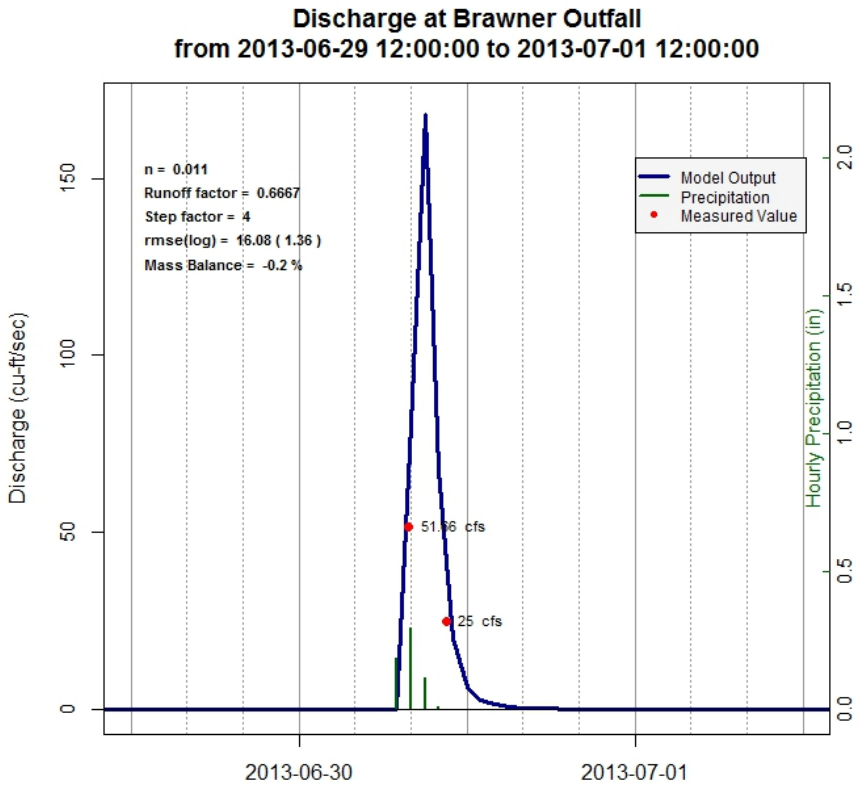
5.3.3 Model Results and Performance

Using the very limited number of calibration target values available, the model achieved an overall Root Mean Square Error (RMSE) for the modeled bacteria concentrations of 0.79 (log base 10). This value represents a lower (better) value than the objective (1 log base 10) stated in the QAPP. The RMSE (bacteria concentration) for the primary basin used for calibration (Brawner Parkway) was 0.74 (log base 10).

As previously discussed, discharge during runoff events in the TMDL study area occurs over a short period of time due to the intensity and brevity of precipitation events and the lack of retention and absorption of runoff provided by the urban land cover. Figures 14 and 16 show simulated discharge at the Brawner and Louisiana outfalls, as well as measured flow values at these outfalls. Figures 15 and 17 show bacteria concentrations at the same locations, respectively, and how concentrations may change several orders of magnitude over a short time period. In general, measured values are usually below the modeled values. In smaller basins like Ropes Park (Figure 18) a very small discharge was measured within three hours of peak discharge. This indicates that in some cases the model may not be routing water as fast as the engineered system transmits it to the bay.

Model predicted discharge had an overall RMSE of 25cfs. However, since the range of discharge values through a runoff event encompassed several orders of magnitude, a log 10 RMSE is probably a more realistic way of evaluating the models ability to forecast discharge. The log 10 RMSE for discharge in the model was 0.56.

Mass balance error for individual sub-watersheds were small (+/- 0.1%) indicating that the runoff generated was being passed completely through the system. Mass balance error for bacteria loads was less than 5%, a value that can be partially attributed to uncertainty in the representation of bacteria decay/regrowth processes.



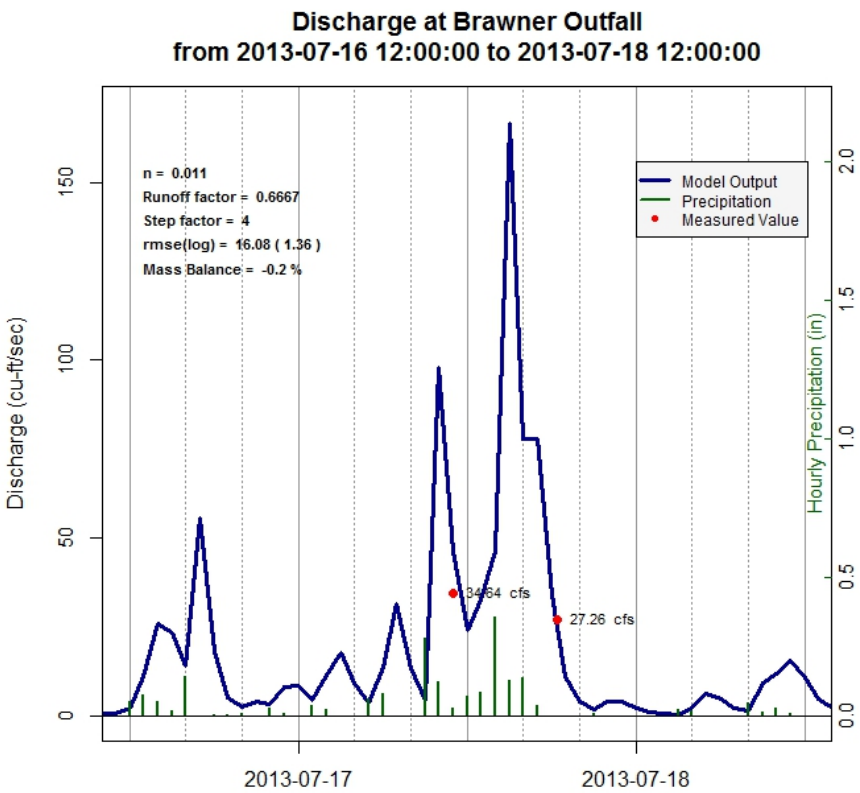
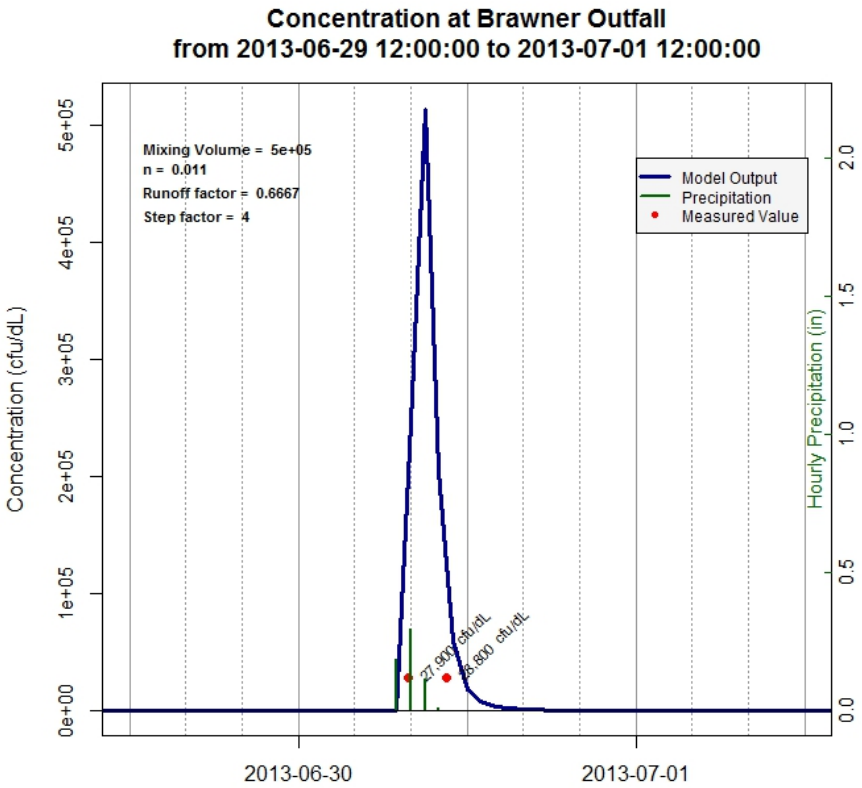


Figure 14. Modeled Discharge, Precipitation and Calibration Points at Brawner Parkway Outfall near Ropes Park on June 30, 2013 and July 17, 2013.



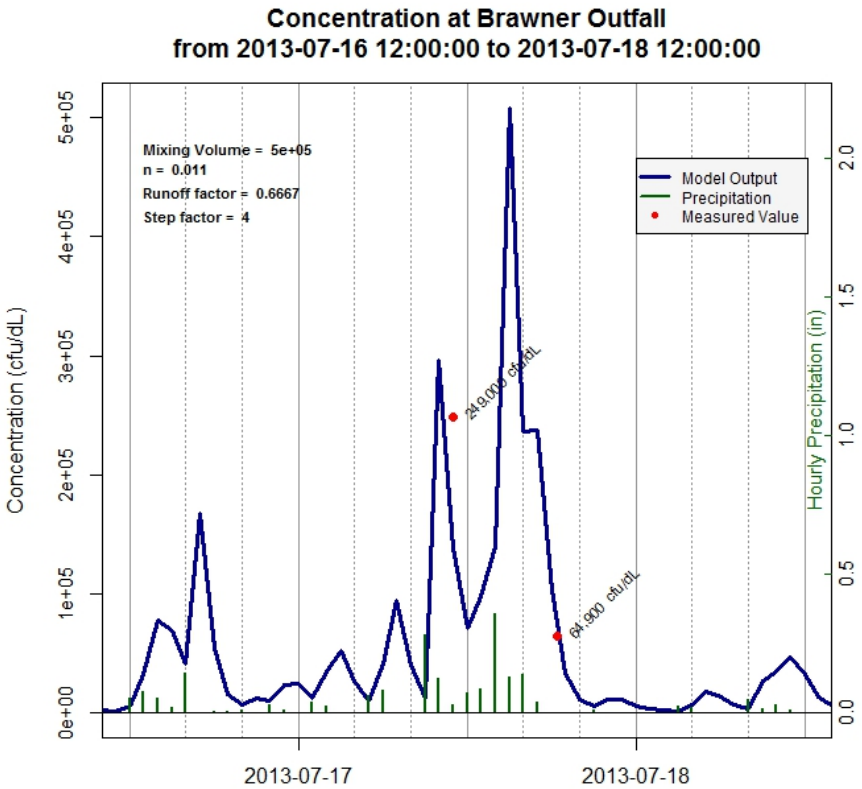


Figure 15. Modeled Bacteria Concentrations, Precipitation and Calibration Points at Brawner Parkway Outfall near Ropes Park on June 30, 2013 and July 17, 2013.

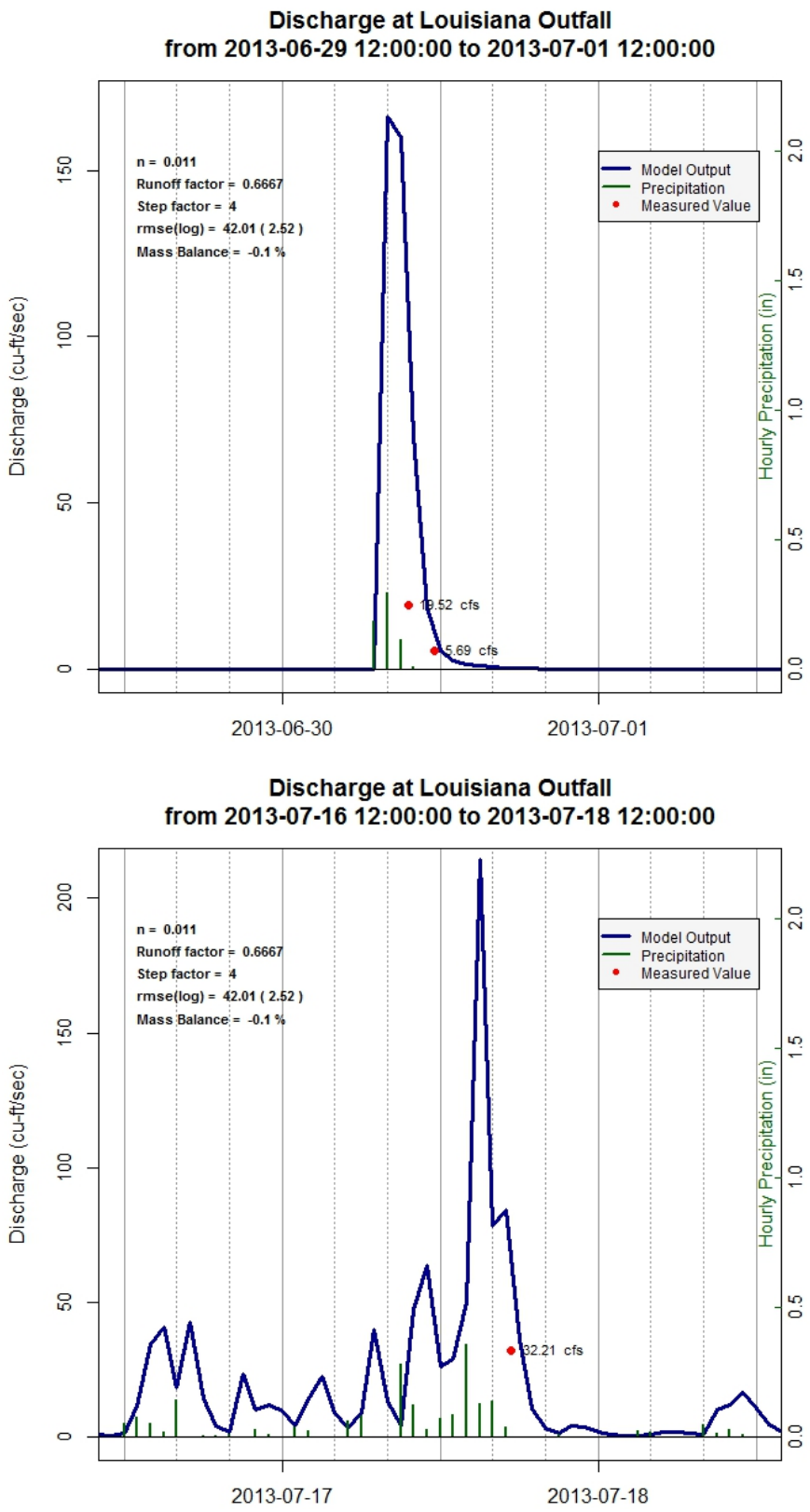
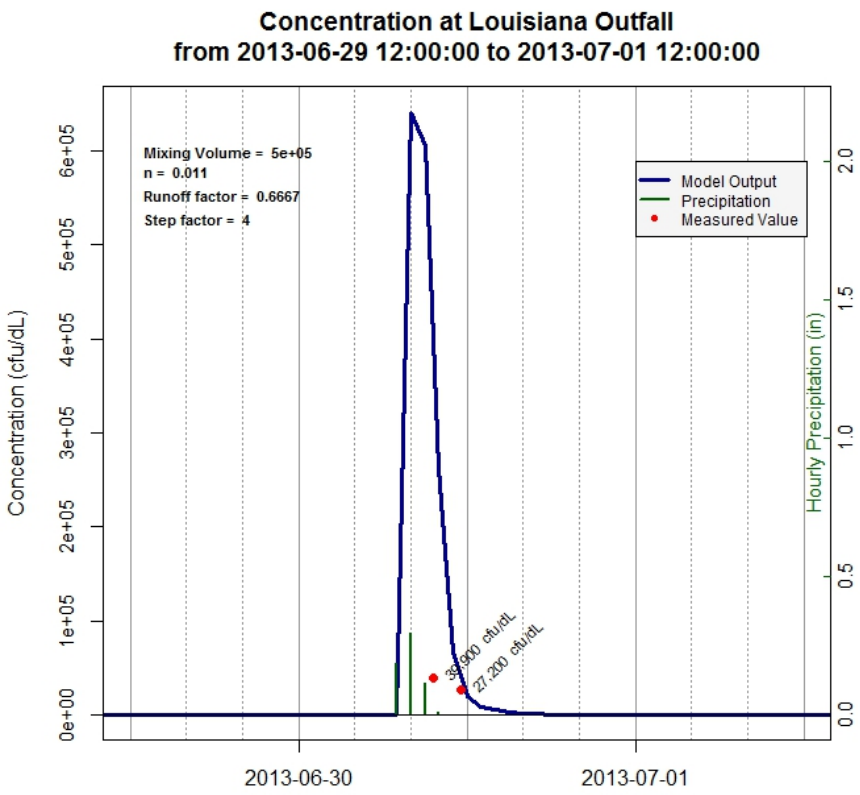


Figure 16. Modeled Discharge, Precipitation and Calibration Points at Louisiana Outfall in Cole Park on June 30 and July 17, 2013.



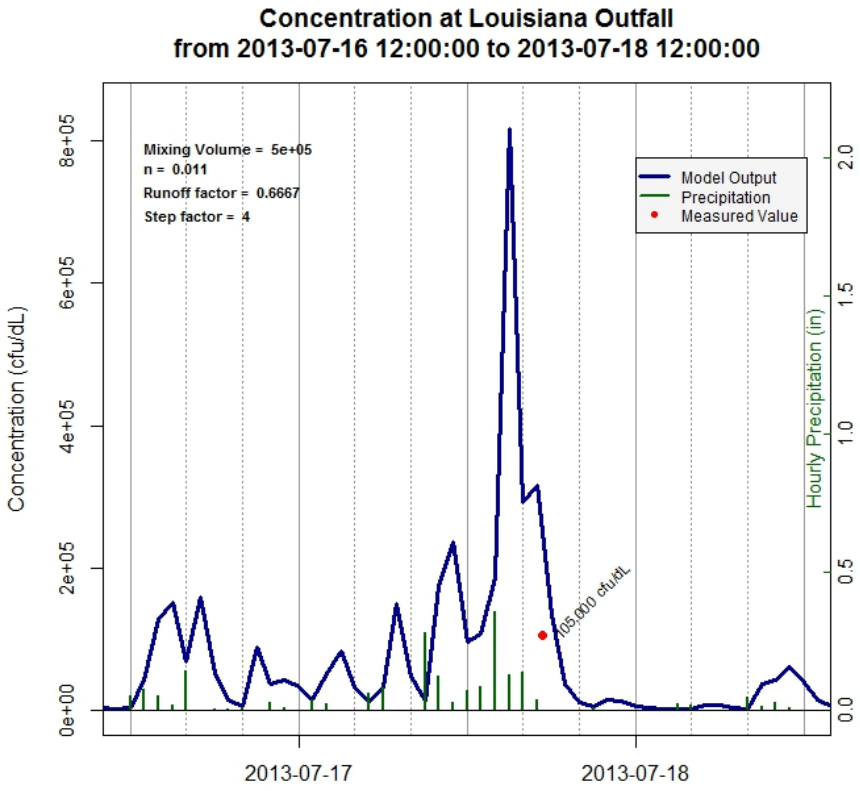


Figure 17. Modeled Bacteria Concentrations, Precipitation and Calibration Points at Louisiana Outfall in Cole Park on June 30 and July 17, 2013.

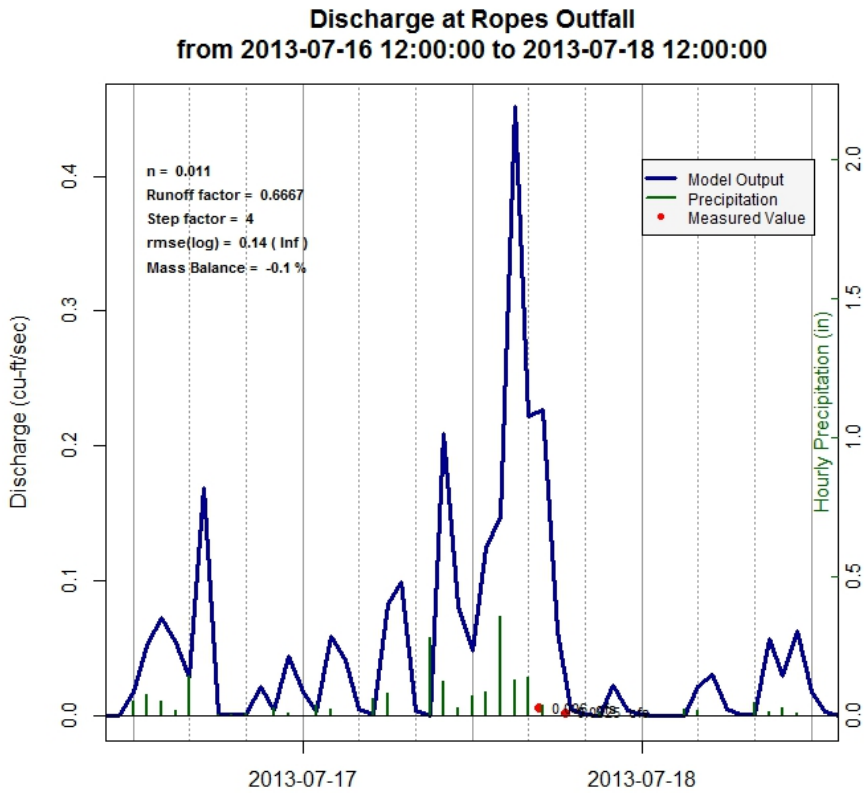


Figure 18. Modeled Discharge, Precipitation and Calibration Points at Ropes Outfall in Ropes Park on July 17, 2013.

5.3.4 Other considerations

Although the model effectively simulated runoff discharge and bacteria loads through the system, the paucity of calibration points limits the robustness of the model. Also, as with any modeling effort, there are certain limitations in the ability of a numerical model to make extremely accurate predictions of natural systems.

5.3.4.1 Model Limitations

This model was developed to simulate flow through a stormwater system and is initiated and driven by precipitation. The model can be used to make predictions about what the range of bacteria concentrations might be when stormwater discharges to the bay. Since the ditches, channels and conduits of the stormwater sewer system are not naturally flowing streams, with components such as base flow to maintain year round flow, there is only water flowing in this system when there is runoff from a precipitation event. So, forecasts of bacteria loading only occur when there has been a precipitation event. As mentioned in previous sections, these flows occur over a very short period of time and it is only over these periods that bacteria concentrations are forecast.

5.3.4.2 Dry weather loads

A review of the data compiled for this TMDL study shows that elevated bacteria concentrations occur at times when there is no runoff discharged to the bay (Figure 9). These values cannot be explained or simulated using the TMDL model developed for this TMDL effort, but they represent a significant contribution to the exceedances reported at Segment 2481CB_03 and 2481CB_04. To examine this phenomenon further, it is best to simplify each segment's bacteria data by aggregating the values collected at multiple SWQM stations, thereby creating a single "synthetic" SWQM station that is made up of the maximum measured bacteria concentrations from all the SWQM stations in the segment.

This synthetic station then, has all the SWQM values that are likely to trigger a beach advisory. A recurrence graph (Figure 19) shows the significance of dry weather loading at Cole Park using the synthetic SWQM station bacteria concentration values. The dry weather measurements in this case are those WQ samples taken more than three days (4 or more days) after a precipitation event.

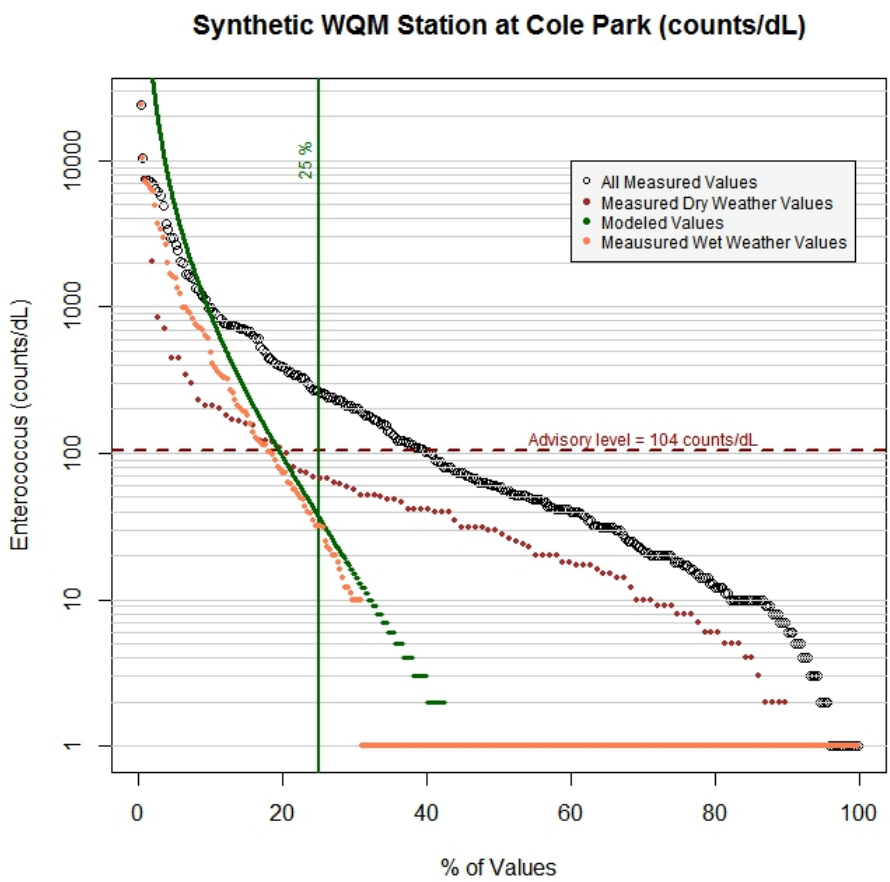


Figure 19. Recurrence graph of a synthetic WQM station representing all WQM stations at Cole Park. Dry weather measurement contributes to frequency of beach advisories issued when concentrations are greater than 104 counts/dL.

In Figure 19, the dry weather values can be seen to exceed the WQ limit of 104 counts/dL almost 20% of the time, while all the measured values for that segment exceed the limit about 40% of the time.

5.3.4.3 Combining measured dry weather values with simulated wet weather values

Comparing the recurrence frequency of bacteria concentrations forecast by the model output to the recurrence frequency of measured bacteria values that only occur during runoff events, it is apparent that the model performs reasonably well in producing concentrations similar to what was measured in the field (Figure 19). By replacing the zero values forecast by the model during periods of no runoff with bacteria values known to occur during dry weather (dry weather loading), a recurrence frequency plot is developed that closely resembles the recurrence frequency of the synthetic SWQM station created for Cole Park (Figure 20). Ropes Park shows similar results (Figure 21).

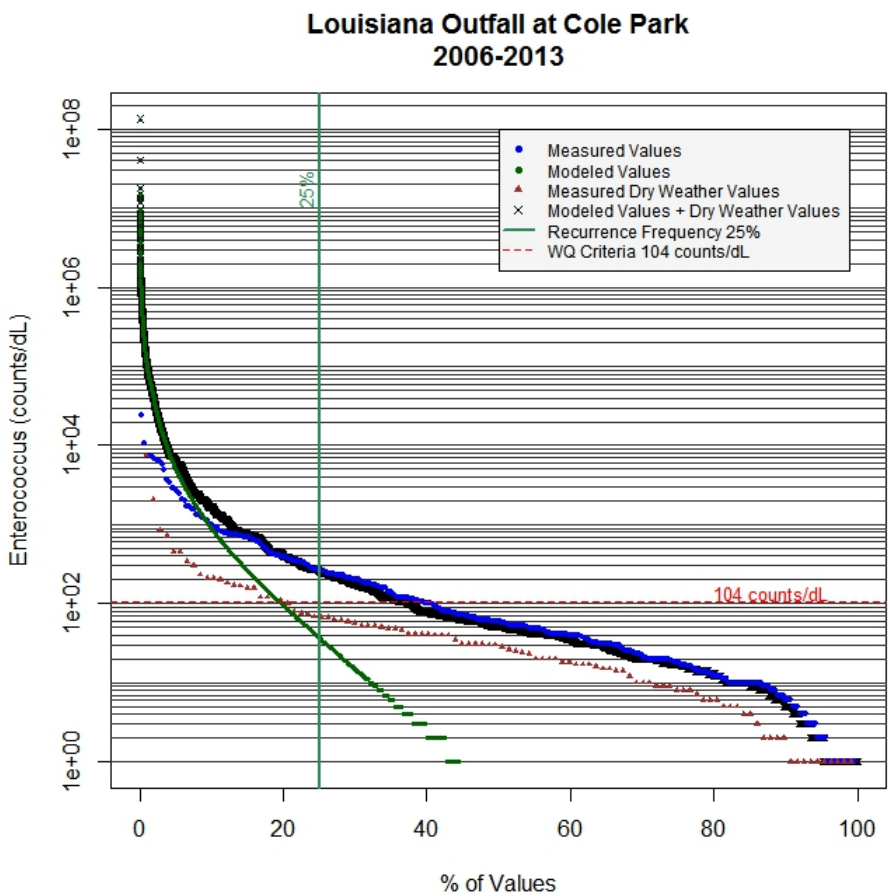


Figure 20. Recurrence graph showing the combination of modeled bacteria concentrations and measured dry weather bacteria concentrations at Cole Park.

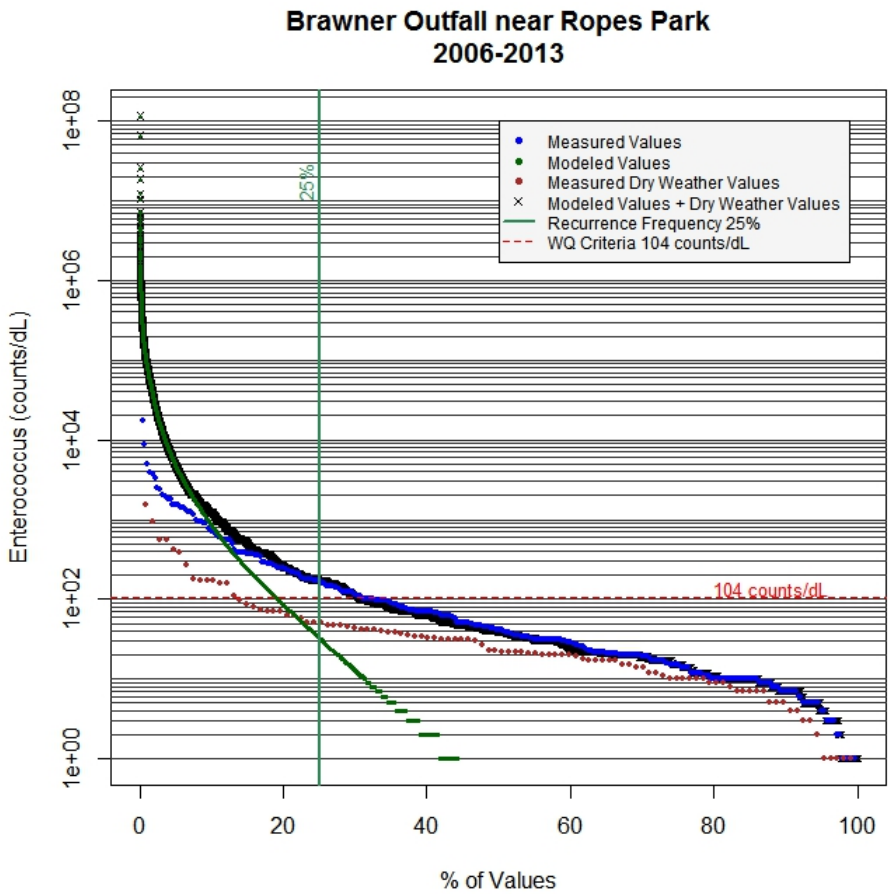


Figure 21. Recurrence graph showing the combination of modeled bacteria concentrations and measured dry weather bacteria concentrations at Ropes Park.

5.3.5 Tertiary calibration using recurrence graph curves.

The results of combing dry weather loading with model results as described in Section 5.3.4.3 also provides a visual affirmation that the character (frequency and distribution) of the bacteria loading values forecast by the TMDL model reflect the same response observed in the natural system. Additional confidence in the ability of this TMDL model to provide realistic load reduction requirements to meet the water quality criteria for Segments 2481CB_03 and 2481CB_04 can be gained by examining Figures 20 and 21 and by noting the closeness of fit in the area of the graphs where the WQ criteria (dashed red line) intersects the compliance frequency of 25%.

5.4 Development of Bacteria TMDLs Using Numerical Modeling

Computations using the numerical model developed for these TMDLs are necessary to derive a percent reduction goal for the TMDL, which is one way of complying with the requirements of TMDL development. The following subsections provide a step-by-

step description of how the TMDLs for Segments 2481CB_03 and 2481CB_04 were developed.

5.4.1 Step 1: Estimate Current Bacteria Loadings.

The model outputs were first summed over 24 hour periods from the smaller one-hour model time steps to provide total daily loads to the bay in counts per day. The model can also be used to generate instantaneous quality values in terms of counts/dL. These two values are used in conjunction to determine the range of concentrations occurring at sampling locations and also the corresponding loading for any given day. When this data is compiled for the entire time period of interest, the percentage of time that single sample criteria are exceeded is calculated and the corresponding loading associated with that exceedance can also be calculated.

There are two components to which the bacteria loading can be attributed (i.e., dry and wet weather loadings), the dry weather component is not well understood and, hence cannot be managed. However, it can be represented in the load reduction process using the method described in Subsection 5.4.5. A pollutant load reduction goal can be calculated by comparing the pollutant loads modeled under current conditions with the modeled loads that are commensurate with staying just below the frequency of exceedance dictated by the contact recreation criteria (i.e., below a 25% exceedance).

5.4.2 Step 2: Estimate TMDL Loadings.

As described above, the TMDL load can be calculated by estimating the watershed loads that correspond to the loading associated with staying just below the exceedance frequency dictated by the contact recreation criteria (i.e., 25%) over the entire time period of interest.

5.4.3 Step 3: Estimate Load Reductions.

After existing loading estimates are computed, load reduction estimates for the sub-watersheds associated with each impaired segment are estimated by calculating the difference between existing loading and the allowable load. Existing and compliance loads were determined using modeling results.

5.4.4 Step 4: Calculate an Explicit Margin of Safety.

An explicit MOS can be calculated by reducing the estimated TMDL loading value to account for uncertainty in the TMDL analysis. This is done by subtracting the TMDL load, estimated using 95% of the single sample contact recreation criterion (i.e., 98.8 counts/dL) from the TMDL load estimated using the full 104 counts/dL criterion.

5.4.5 Step 5: Estimate Load Allocation (LA).

As has been shown in earlier sections, dry weather loading (DWL) is a significant contributor to water quality at both Cole and Ropes Parks. Although the sources of this loading are not well understood, they can be categorized as the non-permitted,

non-point source components of the TMDL. As such, dry weather loading represents the Load Allocation (LA) portion of the TMDL calculation.

DWL to the impaired segments can be estimated if the following factors are known:

1. Area influenced by the DWL,
2. The volume of water in the area of the dry weather load,
3. The median concentration of bacteria in that area, and
4. The decay rate for the bacteria.

5.4.5.1 Area affected by dry weather loading (DWL)

Data collected by CCS provides bacteria concentrations at discrete water depths and distances from the shore at both Cole and Ropes Parks. Figure 22 shows box plots of bacteria concentrations measured at the beaches of Cole and Ropes Parks during dry weather. Examining these box plots, one can see that, at Cole Park, DWL affects only the stations at 0.6 meter depth, which are located between 5 and 29 meters from the shoreline. At Ropes Park, DWL influences water quality in stations at all three depths, with less influence at the deepest station (located 24 meters from the shoreline). From this information, it can be inferred that the areas influenced by DWL are probably best defined by distance from shoreline rather than by water depth. Therefore, conservatively speaking, an average distance from shore of 26.5 meters must contain the majority of the flux from dry weather loading.

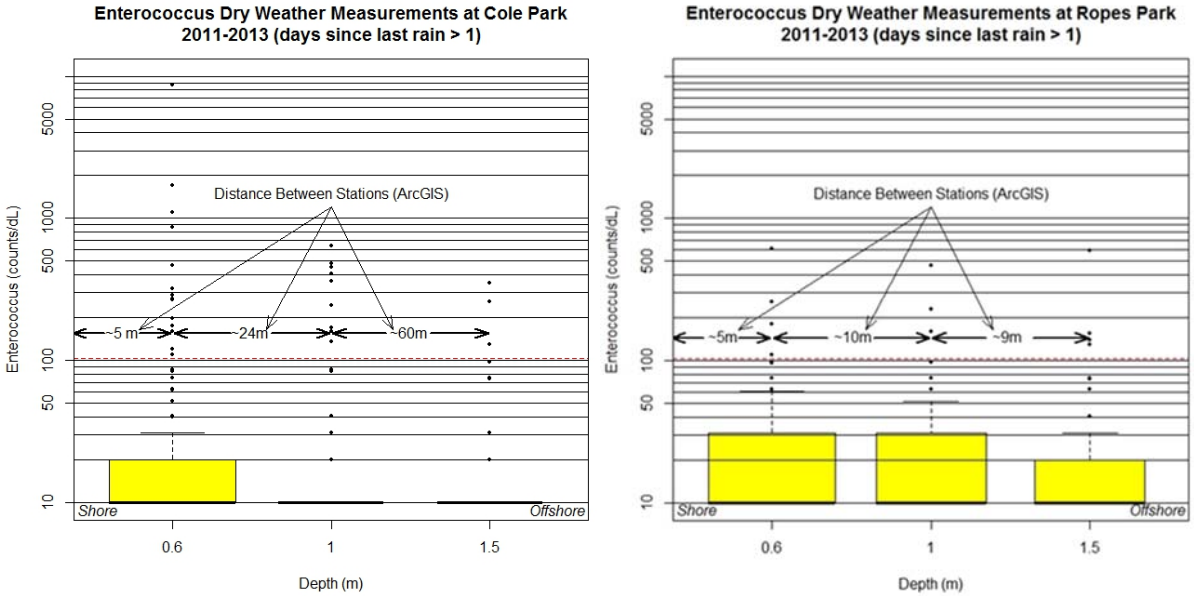


Figure 22. Box and whisker plot of *Enterococcus* concentrations during dry weather by water depth; collected by CCS at their Cole Park SWQM stations.

Using ArcGIS, a polygon was created using an approximation of the shoreline as seen in the 2008-2009 Texas Orthoimagery Project images of the Corpus Christi

Quadrangle's southeast quarter at Ropes and Cole Parks (TNRIS 2015). The seaward edge of the polygon is the paralleled shoreline offset (seaward) by 26.5 meters. These polygons represent the areas influenced by DWL and are referred to as the DWL zones (Figure 23).

A

B

Figure 23. Dry weather loading (DWL) zones in Cole and Ropes Parks (2008-2009 Texas Orthoimagery). NOTE: maps are at different scales.

5.4.5.2 Volume of the DWL zone.

The average depth at a distance of 29 meters from shore at Cole Park is 1 meter. This gives an average slope of 0.034483 m/m. At a distance of 26.5 meters the average depth is 0.914 m. Using Equation 10 with a DWL zone area of 46883 m^2 and depth of 0.914, a volume of 21426 m^3 is calculated for Cole Park.

The average depth at a distance of 24 meters from shore at Ropes Park is 1.5 meters. This gives an average slope of 0.0625 m/m. At a distance of 26.5 meters the average depth is 1.66 m. Using Equation 10 with a DWL zone area of 8629 m^2 and depth of 1.66 m, a volume of 7162 m^3 is calculated for Ropes Park.

Equation 10. Volume of a wedge.

$$V = \frac{1}{2} * A * D$$

Where:

V = volume
A = the amount of water surface in the dry weather loading zone
D = the maximum average depth along the seaward perimeter of the zone

5.4.5.3 Calculating an average decay rate for bacteria at Cole and Ropes Parks

In order to calculate an average decay rate, bacteria measurements collected over consecutive days (or other time consistent interval) are required. There were no consecutive time intervals available during dry weather, however 20 pairs of bacteria concentrations that occurred on consecutive days and were collected at the 0.6m depth interval were selected from the CCS dataset for analysis (Table 16). A decay rate was calculated for each pair and then averaged for each Park. The average decay rate at Cole Park is 2.72 day^{-1} and the average decay rate for Ropes Park is 3.30 day^{-1}. This difference reflects the steeper beach slope at Ropes Park which means that deeper water is closer to the shore allowing for more mixing and settling to occur, thus decreasing bacteria concentrations in the water faster.

5.4.5.4 Calculating bacteria flux from DWL

The median concentrations for dry weather bacteria measurements were extracted from the TGLO water quality monitoring data in a fashion similar to the development of the "synthetic" SWQM station described in Section 5.3.4.2 to represent the median (rather than the maximum) concentration of bacteria in the DWL zone waters on the measurement day. This median concentration was then converted to counts of bacteria present in the DWL zone by multiplying by the volume of water in the DWL zone by the median concentration (converted to counts/m^3). Since the bacteria counts decay over time, the decay rate resulting from the calculations described in Section 5.4.5.3 can be used to estimate the flux of bacteria required to maintain the median concentration by inversing the decay rate (Equation 11).

Equation 11. Inverse Decay.

$$Lo = \frac{Ld}{e^{-Kb*dT}}$$

Where:

Lo = the original load
Ld = the decayed (measured) load
Kb = the decay constant
dT = the elapse time for the decay to occur (1 day)

This calculation was applied to all dry weather data (2006-2013), as described above, for each park. The mean of these flux values represents the average daily load from the unknown source of DWL bacteria loading to each park's DWL zone.

Table 16. Decay rates calculated from data pairs collected at Cole and Ropes Parks where Co is the decay rate original concentration and Cd is the decayed concentration over one day at the same station.

Location	Variable ID	Decay Rate (day^{-1})	Event	Co	Cd
Cole Park	kbc1.1	4.2	1	650	10
Cole Park	kbc1.2	3.0	1	570	30
Cole Park	kbc1.3	4.6	1	10000	98
Cole Park	kbc1.4	3.4	1	6900	230
Cole Park	kbc2.1	6.6	2	7700	10
Cole Park	kbc2.2	2.6	2	1840	138
Cole Park	kbc2.3	1.0	2	138	52
Cole Park	kbc2.4	3.2	2	24196	1010
Cole Park	kbc2.5	1.3	2	1010	266
Cole Park	kbc2.6	2.4	2	8160	776
Cole Park	kbc2.7	1.5	2	776	175
Cole Park	kbc3.1	2.2	3	29100	3260
Cole Park	kbc3.2	2.0	3	3260	431
Cole Park	kbc3.3	0.5	3	3260	1990
Cole Park	kbc3.4	2.3	3	1990	200
Ropes Park	kbr1.1	6.1	1	24196	52
Ropes Park	kbr1.2	3.9	2	24196	512
Ropes Park	kbr1.3	2.8	3	512	31
Ropes Park	kbr1.4	0.8	1	24196	10500
Ropes Park	kbr1.5	2.9	1	10500	591

5.4.5.5 Load Allocation from DWL

For Cole Park, with a decay rate of 2.72 day^{-1} the average daily flux of bacteria required to maintain measured DWL concentrations is 2.728674 x 10^{11} bacteria/day. This represents the LA from DWL at Cole Park.

At Ropes Park, using a decay rate of 3.30 day^{-1}, the average daily flux of bacteria required to maintain measured DWL concentrations is 1.464951 x 10^{11} bacteria/day. This represents the LA from DWL at Ropes Park.

5.4.6 Step 6: Calculate Waste Load Allocation (WLA).

As previously stated, the pollutant load allocation for permitted (point) sources is defined by the Waste Load Allocation (WLA). USEPA guidance includes NPDES-permitted stormwater discharges as permitted discharges and, therefore, part of the WLA. Having estimated the TMDL load (Step 2), calculated a MOS (Step 4) and estimated a LA (Step 5), the WLA is calculated by subtracting the LA and MOS from the TMDL.

SECTION 6
TMDL CALCULATIONS

6.1 TMDL and Load Allocations for Segment 2481CB_03 (Cole Park).

The current average daily load of indicator bacteria generated from the model simulation from 2006 through 2013 (8 years) is 1.790 x 10^{13}. The TMDL for this segment is estimated at 1.007 x 10^{12}, which is the equivalent of a 95.9% reduction in *Enterococcus* load from runoff (Figure 24) and an overall load reduction of 94.4%.

The MOS is 1.790 x 10^{11}, which results from subtracting the TMDL estimated with a WQ criterion of 98.8 counts/dL (95% of the single sample contact recreation criterion) from the TMDL estimated using the full WQ criterion of 104 counts/dL.

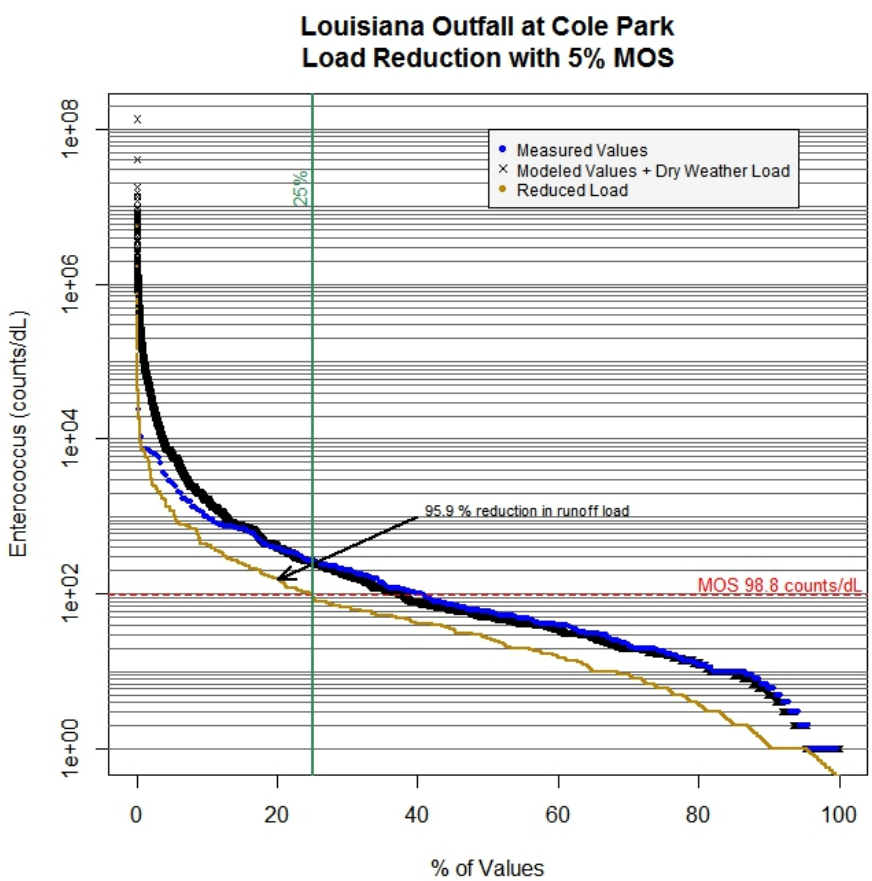


Figure 24. Recurrence graph showing the load reduction necessary for the Cole Park watershed.

The LA_{DWL} is estimated to be 2.730 x 10^{11} and is the result of the analysis presented in subsection 5.4.5 (Step 5) of this document. Since no other non-permitted NPS load is

involved (i.e., the TMDL watersheds are completely urbanized), LA_{DWL} equals the LA for this TMDL.

The $WLA_{stormwater}$ for this segment is calculated to be 5.551 x10^{11} and is the result of subtracting the LA value from the TMDL-MOS value. WLA_{wwtp} is 0, as there are no WWTF outfalls in the TMDL study area. So, the WLA = $WLA_{stormwater}$ = 5.551 x 10^{11}.

TMDL = WLA + LA + MOS

$1.007 \times 10^{12} = 5.551 \times 10^{11} + 2.730 \times 10^{11} + 1.790 \times 10^{11}$

6.2 TMDL and Load Allocations for Segment 2481CB_04 (Ropes Park).

The current average daily load of indicator bacteria generated from the model simulation from 2006 through 2013 (8 years) is 1.6150 x 10^{13}. The TMDL for this segment is estimated at 4.345 x 10^{12}, which is the equivalent of a reduction of a 74.0% in load from runoff (Figure 25) and an overall load reduction of 73.1%.

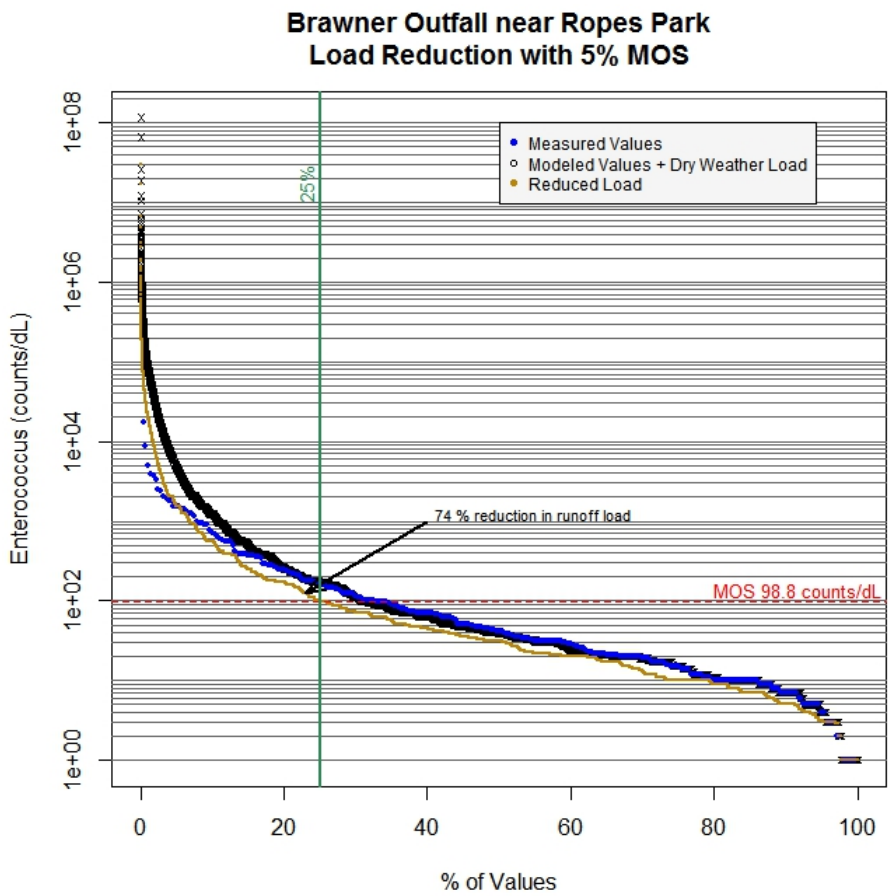


Figure 25. Recurrence graph showing the load reduction necessary for the Ropes Park watershed.

The MOS is 6.622×10^{11}, which results from subtracting the TMDL estimated with a WQ criterion of 98.8 counts/dL (95% of the single sample contact recreation criterion) from the TMDL estimated using the full WQ criterion of 104 counts/dL.

The LA_{DWL} is estimated to be 1.460×10^{11} and is the result of the analysis presented in subsection 5.4.5 (Step 5) of this document. Since no other non-permitted NPS load is involved, $LA_{\text{dry weather load}}$ equals the LA for this TMDL.

The $WLA_{stormwater}$ for this segment is calculated to be 3.537×10^{12} and is the result of subtracting the LA value from the TMDL-MOS value. As in Cole Park, WLA_{wwtp} for Ropes Park is 0, so the total WLA remains 3.537×10^{12}.

TMDL = WLA + LA + MOS

$4.345 \times 10^{12} = 3.537 \times 10^{12} + 1.460 \times 10^{11} + 6.622 \times 10^{11}$

6.3 Estimated Loading and Critical Conditions

USEPA regulations require TMDLs to take into account critical conditions for stream flow, loading, and all applicable water quality standards (40 CFR 130.7(c) (1)). To accomplish this, available SWQM data for the impaired segments were evaluated and the magnitude of water quality criteria exceedance was assessed under warm/cold and wet/dry seasonal conditions. The analysis is presented in sections 2.7 and 2.8 of this document and shows that the majority of exceedances occur during wet and warm weather conditions.

6.4 Allowance for Future Growth

The TMDL watersheds described in this document are in a fully developed urban area that are already serviced by an existing centralized wastewater collection and treatment system. The outfalls for this wastewater treatment system are not located near the TMDL watersheds and are not expected to be moved to locations near the TMDL study area. It is possible that future growth may result in the densification of urban land use in the TMDL watersheds. However, the factors influencing pollutant releases associated with this densification are expected to be controlled by the existing MS4 permit. Therefore, an allowance for future growth has been purposely omitted from these TMDLs.

SECTION 7
PUBLIC PARTICIPATION

The Center for Coastal Studies provided coordination for public participation in this TMDL project and the associated TMDL Implementation Plan (I-Plan) development effort. Public meetings were held approximately every three months in association with the TMDL effort. The meetings introduced the TMDL process, identified the impaired segments and the reason for the impairments, reviewed historical data, described potential sources of bacteria within the watershed, and presented the TMDL analysis, as well as preliminary and final load allocations. These meetings are ongoing and will continue after the TMDL is adopted by the TCEQ as part of TCEQ's adaptive management strategy. In addition to informing the public, the meetings give TCEQ the opportunity to solicit input on the TMDLs and I-Plan from all interested parties within the study area.

To obtain additional information or to provide input on these TMDLs and the associated I-Plan, members of the public should contact the CCS Texas A&M University-Corpus Christi project manager or the TCEQ Project Manager.

SECTION 8
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