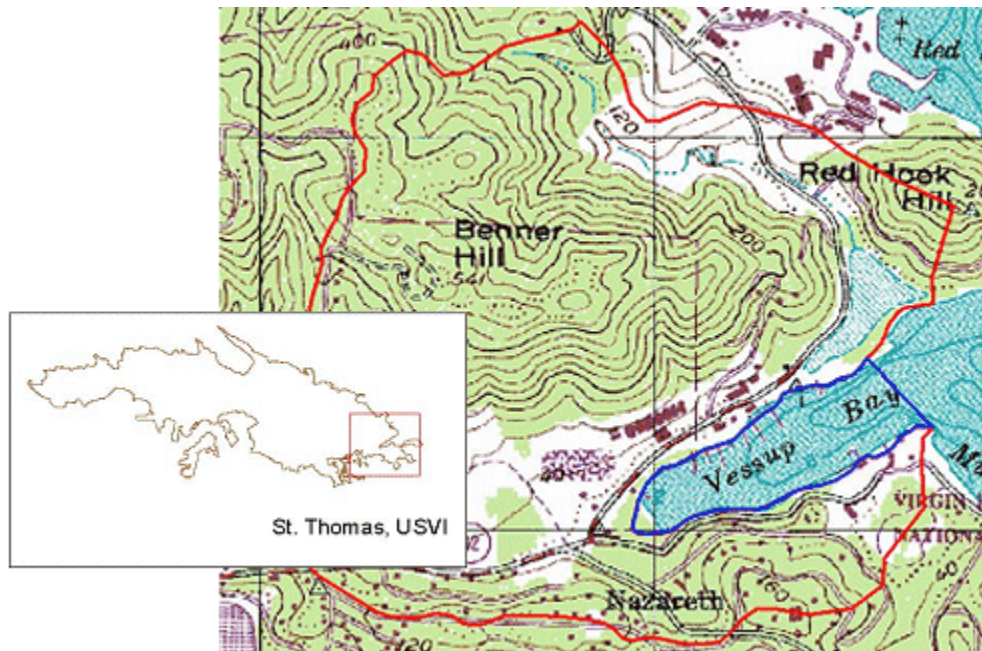


Fecal Coliform Total Maximum Daily Load, Vessup Bay, St. Thomas, United States Virgin Islands



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US Virgin Islands
Department of Planning & Natural Resources
Division of Environmental Protection

Cyril E. King Airport, 2nd Floor
St. Thomas, US Virgin Islands 00802
Phone: (340) 774-3320
Fax: (340) 714-9549



45 Mars Hills, Frederiksted
St. Croix, US Virgin Islands 00841
Phone: (340) 773-1082
Fax: (340) 692-9794

This document was prepared in part by TetraTech, Inc. under EPA contract number 68-C-02-108 – Task Order 85 under the technical direction of:

Antony Tseng
EPA Region 2 – New York
Department of Environmental Planning and Protection
Community & Ecosystems Protection Branch
Fate & Effects Team

Final editing and preparation by:

Anita Nibbs and Christopher Crawford
U.S. Virgin Islands Department of Planning and Natural Resources
Division of Environmental Protection

CONTENTS

CONTENTS	i
LIST OF FIGURES	ii
LIST OF TABLES	ii
1 INTRODUCTION	1
2 PROBLEM IDENTIFICATION	2
2.1 Background	2
2.2 Water Quality Criteria.....	4
2.3 Pollutant Sources	4
2.3.1 Point Sources	5
2.3.2 Nonpoint Sources.....	5
2.4 Current Conditions.....	7
3 DATA ANALYSIS	8
3.1 Bacteria Monitoring Data	8
3.2 Critical Conditions	11
4 ANALYTICAL APPROACH	13
4.1 Loading Model Configuration	13
4.1.1 Vessup Bay WWTP	14
4.1.2 General Land Surface Loading	14
4.1.3 Septic System Failure Loading.....	15
4.1.4 Marina Loading.....	16
4.1.5 Temporal Disaggregation of Load Estimates	18
4.2 Tidal Prism Model	21
4.3 Assumptions and Limitations	22
5 TMDL CALCULATION AND ALLOCATIONS	24
5.1 Numeric Target for Fecal Coliform Bacteria.....	24
5.2 Wasteload Allocations	25
5.3 Load Allocations.....	25
5.4 Margin of Safety	25
5.5 TMDL	26
6 MONITORING RECOMMENDATIONS	28
7 IMPLEMENTATION AND MANAGEMENT	29
7.1 Infrastructure Provision	29
7.2 Policy and Regulation	30
7.3 Design and Practice.....	31
7.4 Education	31
REFERENCES	33
Appendix A: Water Quality Data	36
Appendix B: Tidal Prism Model	37

LIST OF FIGURES

Figure 2-1. The Vessup Bay Watershed and Bay and Assessment Unit.	3
Figure 3-1. Fecal Coliform Criteria for Class B Waters, and All Observed Data from Station STT-22B in Vessup Bay.	8
Figure 3-2. Fecal Coliform Criteria for Class B Waters, and Observed Data less than 75 counts per 100mL from Station STT-22B in Vessup Bay.	9
Figure 3-3. Water Quality Monitoring Stations in the Vessup Bay system.	10
Figure 3-4. Composite Flow-weighted Average FC Concentrations and Flow Percentiles for Stations in Vessup Bay.	12
Figure 4-1. Landuse Distribution in the Vessup Bay watershed.	17
Figure 4-2. Streamflow at USGS Gage 50274000, 1/1/1998 - 9/30/2004.	19
Figure 4-3. Streamflow Accumulation Curve for USGS Gage 50274000, 1/1/1998 - 9/30/2004.	19
Figure 4-4. Daily Percentage of Total 1/1/1998 - 9/30/2004 Flow for USGS Gage 50274000.	20
Figure 4-5. Estimated Loading of Total Fecal Coliform Bacteria to Vessup Bay, 1/1/1998-9/30/2004.	20
Figure 4-6. Tidal Prism Model Concept.	21
Figure 5-1. TMDL Calculation Methodology based on Tidal Prism Model Reduction Scenarios.	25

LIST OF TABLES

Table 2-1. U.S. Virgin Island's 303(d) List of Impairments and Impairment Sources in Vessup Bay.	4
Table 2-2. Pollutant Sources and Estimated Fecal Coliform Bacteria Loads to Vessup Bay.	5
Table 3-1. Statistical Summary of Ambient Fecal Coliform Bacteria Data from STT-22B.	9
Table 3-2. Composite Flow and FC Concentration statistics in Vessup Bay.	12
Table 4-1. Watershed loading from land surface washoff by land use type.	15
Table 4-2. Estimation of Daily Septic System Leakage Contributions based on St. Thomas Census Data.	16
Table 4-3. Calculation of marina loading of fecal coliform bacteria.	16
Table 5-1. Summary of the Vessup Bay TMDL.	27
Table 7-1. Urban Best Management Practice Median Pollutant Removal Efficiency.	31

1 INTRODUCTION

Section 303(d) of the Clean Water Act and the U.S. Environmental Protection Agency's (EPA's) Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for waterbodies that are not meeting their designated uses even though pollutant sources have implemented technology-based controls. A TMDL establishes the allowable load of a pollutant or other quantifiable parameter based on the relationship between pollutant sources and in-stream water quality. A TMDL provides the scientific basis for a state to establish water quality-based controls to reduce pollution from both point and nonpoint sources and restore and maintain the quality of the state's water resources (USEPA, 1991).

EPA Region 2 and the U.S. Virgin Islands Department of Planning and Natural Resources (DPNR) have coordinated a watershed assessment and an analysis of ambient water quality monitoring data to support the calculation of a fecal coliform bacteria TMDL for Vessup Bay, in St. Thomas, U.S. Virgin Islands. Vessup Bay is listed as impaired for fecal coliform bacteria on the U.S. Virgin Island's 2002 and 2004 section 303(d) lists. This document presents the results of the TMDL study and provides the technical basis for the calculation of the TMDL.

2 PROBLEM IDENTIFICATION

2.1 Background

Vessup Bay is a shallow, relatively long, narrow, east-west oriented bay located on the southeastern tip of St. Thomas (Figure 2-1). It is bounded by Red Hook Bay to the northeast and Muller Bay to the southeast and was categorized as a partly enclosed embayment by Schottroff et al. (1992). The bay normally receives an easterly wind. The diurnal tidal range is generally less than one foot, which limits the water exchange in the bays. There is a clockwise gyre that exists in the Vessup Bay, Red Hook Bay and Muller Bay system (Schottroff et al., 1992). Its location, orientation, and shape lead to poor circulation and flushing, making it susceptible to water quality problems.

The watershed surrounding the system is comprised of steep topography in the north and moderately steep topography in the south. The major drainage flow in the watershed is from the west to east along a valley between Banner and Nazareth hills, and from small streams feeding from north to south in the Banner hill area.

Because it is a fairly well protected anchorage, Vessup Bay endures heavy boat use as a mooring/anchorage area and as a major marine transportation nodal point between St. Thomas and St. John. Additionally, the watershed has witnessed a significant increase in residential, commercial, and infrastructural development for the last two decades (Schottroff, 1992). Development has contributed to several water quality issues, such as accelerated building activity and subsequent exposure of easily erodible soils to the elements. The result is significantly more sediment in runoff during rainy periods with eventual deposition in the bay. Development has also increased pollutant loading (from single home septic systems) to groundwater and added volume to the sewage treatment plants in the headwaters of Vessup Bay.

Due to the rapid development and activities in the bay and its watershed, Vessup Bay no longer meets the applicable Class B water quality standards published in Subchapter 186, the Water Quality Standards for Coastal Waters of the U.S. Virgin Islands. As a result, the bay has been listed on the U.S. Virgin Island's 2002 Clean Water Act Section 303(d) lists of impaired waterbodies for "Total Fecal Coliform" (Table 2-1).



Figure 2-1. The Vessup Bay Watershed and Bay and Assessment Unit.

Table 2-1. U.S. Virgin Island's 303(d) List of Impairments and Impairment Sources in Vessup Bay.

Assessment Unit ID	Assessment Unit Name	Class	Impairment	Source
VI-STT-23	Vessup Bay	B	Total Fecal Coliform	Other Marina/Boating On-vessel Discharges Other Recreational Pollution Sources Other Spill Related Impacts Municipal Point Source Impacts from Inadequate Industrial/Commercial Pretreatment

2.2 Water Quality Criteria

The Vessup Bay system is designated as Class B, that is, surface waters intended for propagation and preservation of desirable species of marine life and for primary and secondary contact recreation. The water quality standards stated in Virgin Islands Rules & Regulations title 12, Chapter 7, section 186-3(b)(1-11) that apply to this classification and to the impairment of Vessup Bay are that fecal coliform bacteria concentrations cannot exceed a geomean (log) concentration of 70 fecal coliforms/100mL by MF or MPN count.

The geomean (or geometric mean) component of this criterion requires the calculation of the geometric mean of all samples taken at any given sample site at that given time. Due to the frequency of the sampling program (e.g. quarterly), USVI's water quality assessments are based on whether 10% of the samples exceed 70 colonies/100 mL per site per day as being impaired. This methodology is more stringent than that the geometric mean based on the data available. However, due to the fact that DPNR only samples quarterly, there isn't enough data to statistically say for sure how stringent this rule is since a 90th percentile value cannot be meaningfully derived. This is the water quality target identified for determination of the TMDL. This is the water quality target identified for determination of the TMDL.

2.3 Pollutant Sources

Potential sources that contribute fecal coliform bacteria can be grouped into two categories: point and nonpoint sources. Point sources include discrete, permitted sources that were calculated based on Territorial Pollutant Discharge Elimination System (TPDES) limits for each facility. Nonpoint sources are diffuse and include watershed contributions (e.g., stormwater runoff and septic contributions; estimated based on 2000 Census population data) and local sources (e.g., boat discharges calculated based on a USVI Clean Vessel Act survey data and other activities contributing directly to the bay itself or along the periphery). The sources of fecal coliform bacteria to MLBB are quantified (as daily loads) in Table 2-2 and are further discussed in the following subsections.

Table 2-2. Pollutant Sources and Estimated Fecal Coliform Bacteria Loads to Vessup Bay.

Source	TPDES Permit #	Estimated Average Daily FC Load (#/day)
Point Sources		
Vessup Bay WWTP	VI0020133	2.62E+08
Nonpoint Sources		
Septic System Failures	N/A	1.47E+11
Boat Discharges		
Vessup Bay	N/A	2.09E+08
TOTAL		1.47E+11

2.3.1 Point Sources

There is one active wastewater treatment plant (WWTP) contributing fecal coliform bacteria to Vessup Bay. The Vessup Bay WWTP is located on Benner Hill, approximately 0.5 miles from the Assessment Unit. The Vessup Bay WWTP is permitted to discharge 0.099 million gallons per day (MGD) with a maximum fecal coliform concentration of 70 fecal coliforms/100mL. No documentation of releases beyond permit limits is available, and any additional quantity discharged cannot be estimated due to a lack of data (Anita Nibbs, DPNR; personal communication, May 12th, 2004). Given the short duration of discharge and the proximity to the area of impairment, it is believed that intermittent failures do not significantly increase fecal coliform bacteria concentrations in the Bay. Section 2.3.2.3 will discuss this pollution source in more detail. No permitted municipal separate storm sewer systems (MS4s) exist within the study area.

2.3.2 Nonpoint Sources

Nonpoint sources are considered diffuse sources of pollution. They may contribute to a waterbody due to rainfall-runoff processes or diffusely during dry conditions. Direct, diffuse discharges directly to Vessup Bay are also considered nonpoint sources for the purpose of this study. A lack of previous research exists regarding identification and quantification of specific fecal coliform bacteria sources within the Vessup Bay watershed. Information identifying relationships between sources and in-stream water quality for Vessup Bay are not available either. The following subsections describe potential sources of fecal coliform bacteria to waters of St. Thomas and identify likely contributors to Vessup Bay. These sources are ultimately used as the basis for load estimation and TMDL determination.

2.3.2.1 Agriculture

Agricultural land, which typically consists of cropland, pastureland, and refined animal management, does not exist in the Vessup Bay watershed. No acreage is classified as agricultural land based on land use data circa 1999 obtained from the University of Virgin Islands Eastern Caribbean Center Conservation Center Land Use Inventory.

2.3.2.2 *Urban Runoff*

Urban areas are generally characterized by higher percentages of impervious land due to cover of the land surface by pavement, concrete, and buildings. Higher percentages of impervious area, if not properly managed, result in higher surface runoff potential due to the reduced ability of water to infiltrate into the ground during rainfall events. As water runs the land and paved surfaces, debris and pollutants such as fecal coliform bacteria are entrained and subsequently flow into storm drains and ditches which lead to local coastal water bodies. Harmful bacteria and viruses from pet wastes carried by urban runoff to a waterbody, can contribute to shellfish contamination, harm other aquatic life and threaten human health. Studies have shown that fecal coliform bacteria levels are typically high in urban runoff (USEPA, 2001), and thus may be a significant source of pollution to Vessup Bay. As identified above, no permitted MS4s exist in the study area.

2.3.2.3 *Wastewater Disposal*

In addition to the Vessup Bay WWTP and urban runoff contributions, other opportunities for contribution of fecal coliform bacteria from human waste to Vessup Bay include:

- Unsolicited discharges of untreated wastewater (e.g., patrons of marina facilities),
- Groundwater transport of leachate to a waterbody from failed septic systems, and
- Leaking sewage mains.

Within Vessup Bay, marinas and moored boats are a potential source of bacteria. These sources may be present always or may be transient (e.g., marina use and a subsequent short-term increase in bacteria loading may occur during fishing tournaments). Illicit discharges from marinas are a concern based on the estimate that 50% of live-aboard boats at marinas in the Virgin Islands discharge the contents of their holding tanks directly to surface waters (Mangrove lagoon/Benner Bay BOD TDML, 2003). Based on the sheltered location of the marina and reduced exposure to freshwater and tidal inflows, fecal coliform bacteria discharged from boats in the vicinity of the marina may have a significant impact on bacteria levels in the bay. Marina contributions are estimated in the 4.1.1 Pollutant Representation section of this report.

Residential septic systems treat human waste using a collection system that discharges liquid waste into the soil through a series of distribution lines that comprise the drain field. Fecal coliform bacteria naturally die-off as the effluent percolates through the soil to the groundwater. These systems effectively remove fecal coliform bacteria when properly installed and maintained. A septic system failure occurs when there is a discharge of waste to the soil surface where it is available for washoff into surface waters. Failing septic systems can deliver high bacteria loads to surface waters, depending on the proximity of the discharge to a waterbody and the timing of rainfall events. Septic system failures typically occur in older systems that are not adequately maintained with periodic sewage pump-outs.

Septic system failure may be a significant source of fecal coliform bacteria in the Vessup Bay watershed, based on census data for the region. The area-weighted population of the

Vessup Bay watershed in 2000 was 1,295, based on Census 2000 data for St. Thomas. The Census data show that in 2000, 39.6% of the population of St. Thomas was unsewered (area-weighted to the Vessup Bay watershed, 513 individuals would be unsewered). To calculate a fecal coliform bacteria load from failing septic systems, a 10% failure rate was assumed (Mangrove Lagoon/ Benner Bay BOD TMDL (2003)), as well as an attenuation factor where 10% of the load from failed septic reaches the bay. A production rate of 70 gallons of septic discharge/person/day (Horsley and Witten, 1996) was used to develop a population-based estimate. Horsley and Witten (1996) estimated that septic system discharge contains a concentration of 10,000 CFU/100mL. Based on these estimates, approximately 1.36E+09 fecal coliforms are discharged into the watershed on an average day, and 1.36E+08 fecal coliforms (10% of the discharged load) reach the bay on a daily basis.

No information was available regarding the sewage main leakages in the watershed. For the purposes of this TMDL, sewage main leakage is not assumed to be a source of bacteria to Vessup Bay.

2.3.2.4 *Background Conditions*

Background fecal coliform bacteria loads are from non-human, natural sources. Their contributions can be directly to a waterbody or to the watershed surface where they are ultimately carried to a waterbody. Watershed contributions can be estimated from water quality data collected at headwater stations where the contributing land consists almost entirely of natural landscape with little or no human influence. However, no headwater stations of this type exist for the Vessup Bay study area. Native bird and mammal populations residing in and around the bay may contribute fecal coliform bacteria directly to the bay. Similarly, flocks of native or migrating birds may land in the bay for a short time, and contribute to the bacteria load before departing.

2.4 **Current Conditions**

The TMDLs for Vessup Bay were developed based on conditions that existed from 1998 to 2004. This time frame is concurrent with the majority of the available ambient water quality data. Although data were collected over a significant time frame, the quarterly interval used in the water quality monitoring program does not allow insight to suggest improvement or deterioration over this time period. Section 3 summarizes the available data.

3 DATA ANALYSIS

3.1 Bacteria Monitoring Data

Vessup Bay is an estuarine system that suffers from elevated fecal coliform bacteria concentrations. Figure 3-1 presents the available fecal coliform bacteria concentration data within Vessup Bay from station STT-22B (Vessup Bay). Table 3-1 presents a summary of the data, including the number of samples, average value, minimum value, and maximum value. The approximate DPNR monitoring locations for the data are presented in Figure 3-2. These locations are based on the EPA STORET database coordinates and were verified by DPNR staff.

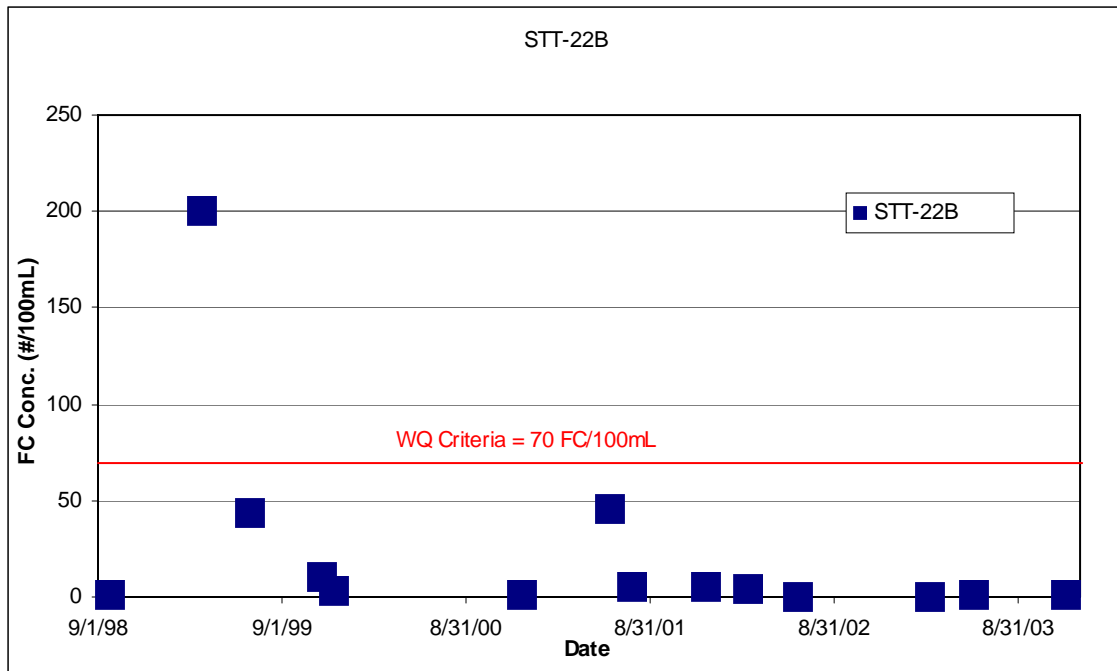


Figure 3-1. Fecal Coliform Criteria for Class B Waters, and All Observed Data from Station STT-22B in Vessup Bay.

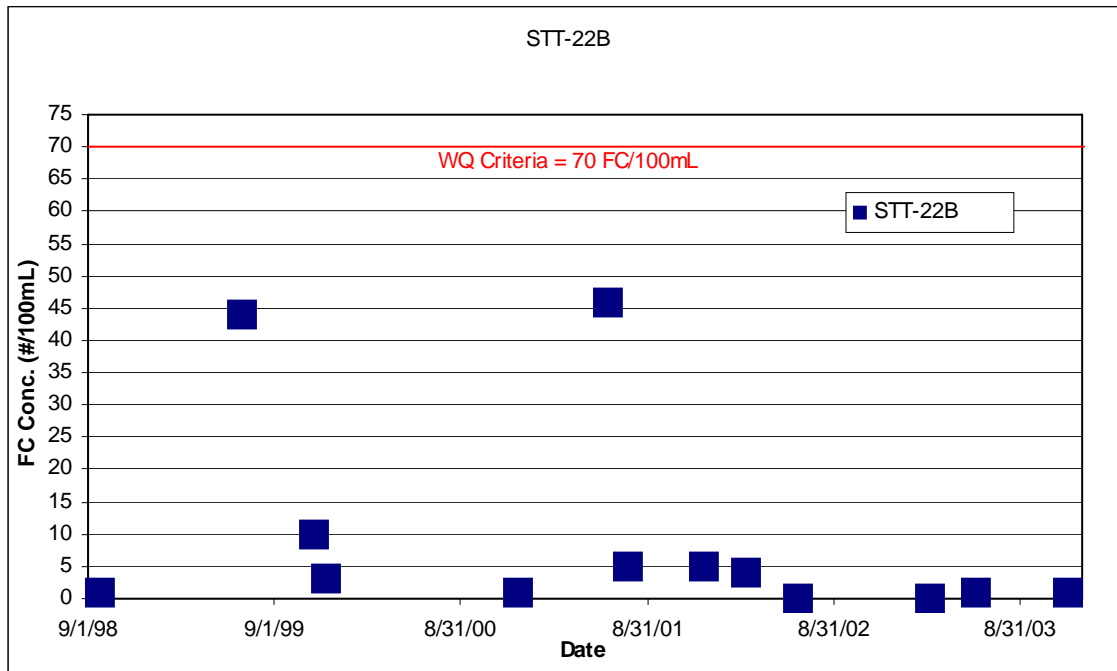


Figure 3-2. Fecal Coliform Criteria for Class B Waters, and Observed Data less than 75 counts per 100mL from Station STT-22B in Vessup Bay.

Table 3-1. Statistical Summary of Ambient Fecal Coliform Bacteria Data from STT-22B.

	Sample Size (n)	Minimum Value (mg/L)	Maximum Value (mg/L)	Number of Samples > 70cts/100mL	Period of Record
Vessup Bay (STT-22B)	16	ND	200	1	9/25/98-8/25/04



Figure 3-3. Water Quality Monitoring Stations in the Vessup Bay system.

3.2 Critical Conditions

The goal of the TMDL is to determine the assimilative capacity of a waterbody based on prescribed water quality standards and to identify potential allocation scenarios that enable the waterbody to achieve the standards. The critical condition is the set of environmental conditions for which controls designed to protect water quality will ensure attainment of objectives for all other conditions. This is typically the period of time in which the impaired water body exhibits the most vulnerability.

The U.S. Virgin Islands experience two seasons, the dry season and the rainy season. The rainy season actually occurs twice a year, with the major rainy season occurring from approximately August to December and a short less significant rainy season occurring around May. Available data for Vessup Bay were evaluated with respect to seasonality to identify possible trends and critical conditions. Due to the quarterly frequency of sampling and limited number of samples (16 total samples from STT-22B), however, seasonal trends were not apparent. The only fecal coliform bacteria sample greater than 70 fecal coliforms/100mL occurred on March 25th, 1999 (it was 200 FC/100mL). The remainder of samples were 50 fecal coliforms/100mL or below.

Flow data can be used to identify whether elevated bacteria levels occur during rainfall events (and are likely watershed-driven) or during dry conditions. Unfortunately, no flow data were available within the watershed to support a correlative analysis between the monitoring data and flow levels. Although flow data were not available within the Vessup Bay watershed, it should be noted that the 200 FC/100mL sample collected on March 25th, 1999 coincided with a relatively high flow at the Turpentine Run gage at Mt. Zion (USGS 50274000 – on St. Thomas). It should also be noted that an analysis between flow and fecal coliform bacteria was conducted for the Mangrove Lagoon watershed on St. Thomas to support a general lack at data and station locations in Vessup Bay. This analysis indicated a relatively strong relationship between flow and elevated bacteria levels in the Mangrove Lagoon/ Benner Bay system, but to a lesser degree in Vessup Bay itself due to sparse data (Table 3-2 and Figure 3-3). Rainfall events typically resulted in higher in-bay bacteria concentrations.

In the absence of sufficient flow and bacteria monitoring data to perform a correlative analysis between flow and bacteria levels, it is assumed that conditions in Vessup Bay are also strongly influenced by rainfall events (and thus watershed-based contributions). Thus, critical conditions occur at high flow conditions. The TMDL analytical framework (further described in subsequent sections) predicts in-bay bacteria concentrations based on all sources present. The 90th percentile in-bay bacteria concentrations predicted by a Tidal Prism model of the bay (which are a result of the 90th percentile flows occurring in the watershed) were considered the critical condition. This level coincides with the TMDL target identified for fecal coliform bacteria, as described earlier in this document, which allows 10% of water quality samples to exceed the 70 fecal coliforms per 100mL level. It should be noted that the TMDL analytical approach considers all conditions for TMDL development, not only the critical condition. It also considers dry condition sources in addition to rainfall-driven sources.

Table 3-2. Composite Flow and FC Concentration statistics in Vessup Bay.

Location: STT-22B Vessup Bay
 Flow Gage: USGS50274000 (cfs)
 Pollutant: Fecal Coliform (#/100 mL)
 Data from: 9/25/1998 to 8/25/2004 (16 Observations)

Flow Range Percentile	# Obs Count	Flow (cfs)			Concentration (#/100mL)		
		Mean	Min	Max	Mean	Min	Max
0-10	2	0.0	0.0	0.1	46	0	46
10-20	1	0.1	0.1	0.1	5	5	5
20-30	2	0.2	0.1	0.2	1	0	1
30-40	1	0.2	0.2	0.2	4	4	4
40-50	2	0.2	0.2	0.3	0	0	1
50-60	2	0.4	0.3	0.5	20	5	44
60-70	1	0.9	0.9	0.9	1	1	1
70-80	1	1.0	1.0	1.0	200	200	200
80-90	2	1.2	1.1	1.3	1	0	1
90-100	1	1.6	1.6	1.6	3	3	3

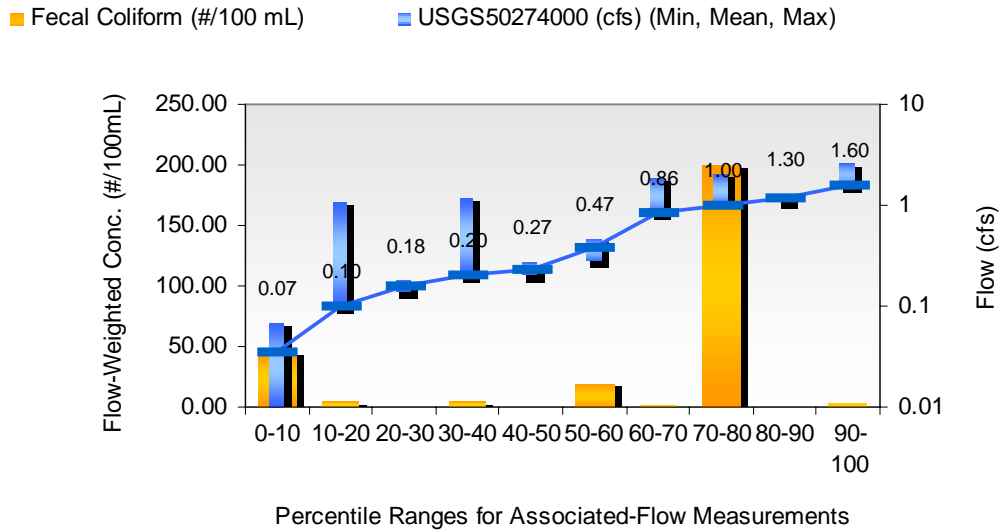


Figure 3-4. Composite Flow-weighted Average FC Concentrations and Flow Percentiles for Stations in Vessup Bay.

4 ANALYTICAL APPROACH

In order to support TMDL development objectives and evaluate the linkage between bacteria sources and the bay's response, an analytical framework combining a tidal prism model of Vessup Bay and a simplified loading model for the watershed and other potential sources was implemented. This approach was selected based on an evaluation of technical, regulatory, and user criteria (Mao, 1992).

Technical criteria refer to the model's capability of simulating the physical system in question, including watershed and/or receiving water characteristics/processes and constituents of interest. Technical criteria used to select an appropriate analytical methodology also included monitoring data availability (water quality and flow data for the watershed and receiving water), the sampling interval of monitoring data, and source identification data. Regulatory criteria make up the constraints imposed by regulations, such as water quality standards or procedural protocol. The evaluation of regulatory criteria was also based on ability to acknowledge EPA's TMDL support elements. User criteria comprise the operational or economical constraints imposed by the end-user and include factors such as hardware/software compatibility and financial resources.

4.1 Loading Model Configuration

In order to evaluate the influence of point and nonpoint bacteria sources on Vessup Bay, a simplified spreadsheet loading model was developed. The model estimates annual bacteria loads to the bay from the watershed and local sources and disaggregates these loads into daily loads for a higher scale of temporal resolution within the bay.

As identified in Section 2.3, key sources of fecal coliform bacteria loading to Vessup Bay include the Vessup Bay WWTP, urban runoff, wastewater disposal (including other recreational pollution sources, other spill-related impacts, municipal point source impacts from inadequate industrial/commercial pretreatment, and other marina/boating on-vessel discharges as identified in the 2004 303(d) list), and background sources. Although field verification data for these sources are not available, information obtained through personal communication with DPNR staff has been supplemented with watershed information (e.g., population estimates, marina characteristics, etc.) to derive bacteria loading estimates for Vessup Bay. These estimates were derived through the development of a spreadsheet model that quantifies loads from individual sources. The sources were regrouped into the following categories to investigate the relative influence of each source and to conduct allocation scenarios to support the implementation process:

- Vessup Bay WWTP
- General land surface loading (including urban runoff and background runoff)
- Septic system failure loading
- Marina loading

4.1.1 Vessup Bay WWTP

The Vessup Bay WWTP is a minor point source facility located in the Vessup Bay watershed. It is permitted to discharge through the Territorial Pollutant Discharge Elimination System (TPDES) program. The facility's fecal coliform bacteria discharge limit is 70 cfu/100ml and it has a design flow of 0.099 MGD. A constant loading was represented for this facility in the model using these limits.

4.1.2 General Land Surface Loading

The bacteria loading spreadsheet considers fecal coliform bacteria loading estimates from the land surface of the watershed, based on the distribution of land use. Land use data are necessary to represent variability in pollutant loading, which is highly correlated to land practices. The basis for this distribution was provided by land use coverage of the Vessup Bay watershed, as shown in Figure 4-1. Land use data used to estimate land surface contributions of fecal coliform bacteria were obtained from the University of Virgin Islands (UVI)- Eastern Caribbean Center- Conservation Center Land Use Inventory.

Sources of bacteria accumulation on the land surface include pets (e.g., dogs, cats, etc.) and wildlife (e.g., birds, rodents, etc.). Bacteria-containing waste is deposited on the land surface of the watershed and then washed off during rainfall events into adjacent streams and ultimately Vessup Bay. Accumulation rates vary among land use categories based on the sources present.

The land surface loading estimates were derived from the Watershed Treatment Model (WTM), which provides annual scale loading estimates of fecal coliform bacteria (Caraco, 2001). The WTM model is a spreadsheet that considers watershed characteristics such as land use distribution, stream network length in the watershed, and annual rainfall. These watershed characteristics were applied to the WTM model, while keeping the default WTM coefficients and concentrations constant based on a lack of site-specific information. Fecal coliform bacteria loading rates to each assessment unit are shown in Table 4-1.

Table 4-1. Watershed loading from land surface washoff by land use type.

Land Use	WTM Land Use Category	WTM Coefficient [annual rate/acre]	Acres	Fecal Coliform Load to Vessup Bay (STT-23) [annual #/yr]
Low density residential	Residential Lands	122E+9	66.77	8.12E+12
Medium density residential		195E+9	72.93	1.42E+13
High density residential		283E+9	3.91	1.11E+12
Waterfront/marine, public facilities, parks/rec/open space, and retail commercial	Commercial Lands	569E+9	52.77	3.00E+13
Undeveloped	Vacant	0	267.29	0.00E+00
TOTAL ANNUAL FC LOAD				5.35E+13
TOTAL DAILY FC LOAD				1.47E+11 [FC/day]
Note: Loading rates are obtained from the "primary sources" worksheet of the WTM spreadsheet (Caraco, 2001).				

4.1.3 Septic System Failure Loading

Septic failure contributions of fecal coliform bacteria were also incorporated into the estimate of the watershed load. Table 4-2 tabulates the septic failure calculations used for the Vessup Bay watershed. Area-weighted calculations, based on 2000 census data, estimated the population in the Vessup Bay watershed to be 1,295. The 2000 Census for St. Thomas also identifies 24,030 housing units on the island, with 9,514 of these units on septic systems. It is estimated, based on the ratio of sewerred to unsewerred households on St. Thomas, that approximately 39.6% of the population (513) is serviced by on-site septic systems. Based on these estimates, approximately 1.36E+09 fecal coliforms are discharged into the assessment unit watersheds on an average day, and 1.36E+08 fecal coliforms reach the assessment unit (bay itself) on a daily basis. This calculation assumes a 10% failure rate and that 10% of the failed quantity is discharged to the bay, addressing in-stream attenuation (Mangrove Lagoon/ Benner Bay BOD TMDL (2003)).

Table 4-2. Estimation of Daily Septic System Leakage Contributions based on St. Thomas Census Data.

	Square KM (NOAA, USGS)	Population (2000 Census for St. Thomas, watershed population was area-weighted)	Population on Septic (2000 Census for St. Thomas)	Population on Failed Septic (2000 Census for St. Thomas)	Volume production/p erson/day (Horsley and Witten, 1996) (gal/day)	Failed Volume (100mL/day) (Mangrove Lagoon/ Benner bay TMDL, 2003)	Failed Load from Septic Systems (Horsely & Whitten, 1996) (#/day)	Daily FC Load to the Bay (#/day)
Vessup Bay (STT-23)	1.88	1,295	513	51	70	135,857	1.36E+09	1.36E+08

It also assumes 70 gallons of septic discharge/person/day at a concentration of 10,000 CFU/100mL (Horsley and Witten, 1996).

4.1.4 Marina Loading

In addition to watershed-based sources of fecal coliform bacteria, there are bacteria loads associated with direct discharge from boats into Vessup Bay. The bacteria load from illicit wastewater discharge in marinas was estimated based on a 2002 DPNR survey of the number of slips for boats within Vessup Bay. A total of 138 slip and mooring permits were recorded for Vessup Bay. Illicit discharges from marinas in the Vessup Bay system are a concern based on the estimate that 50% of live-aboard boats at marinas in the USVI region discharge the contents of their holding tanks directly to surface waters (Mangrove lagoon/Benner Bay BOD TDML, 2003). Based on the sheltered location of the marinas and reduced exposure to freshwater and tidal inflows, fecal coliform bacteria discharged from boats within Assessment Unit STT-23 may have a significant impact on bacteria levels. The calculations and assumptions for daily loading estimates are shown in Table 4-3.

Table 4-3. Calculation of marina loading of fecal coliform bacteria.

	Slip permits	50% of boats dump illegally	Dumped Gallons/week. (1.4 purges of 40 gallon tank)	Dumped gallons/day (Dumped Gallons/7)	Calculated FC: #/day based on 10,000/100mL
Unit boat	1	0.5	28	4	1.51E+06
Vessup Bay (STT-23)	138	69	3,864	552	2.09E+08

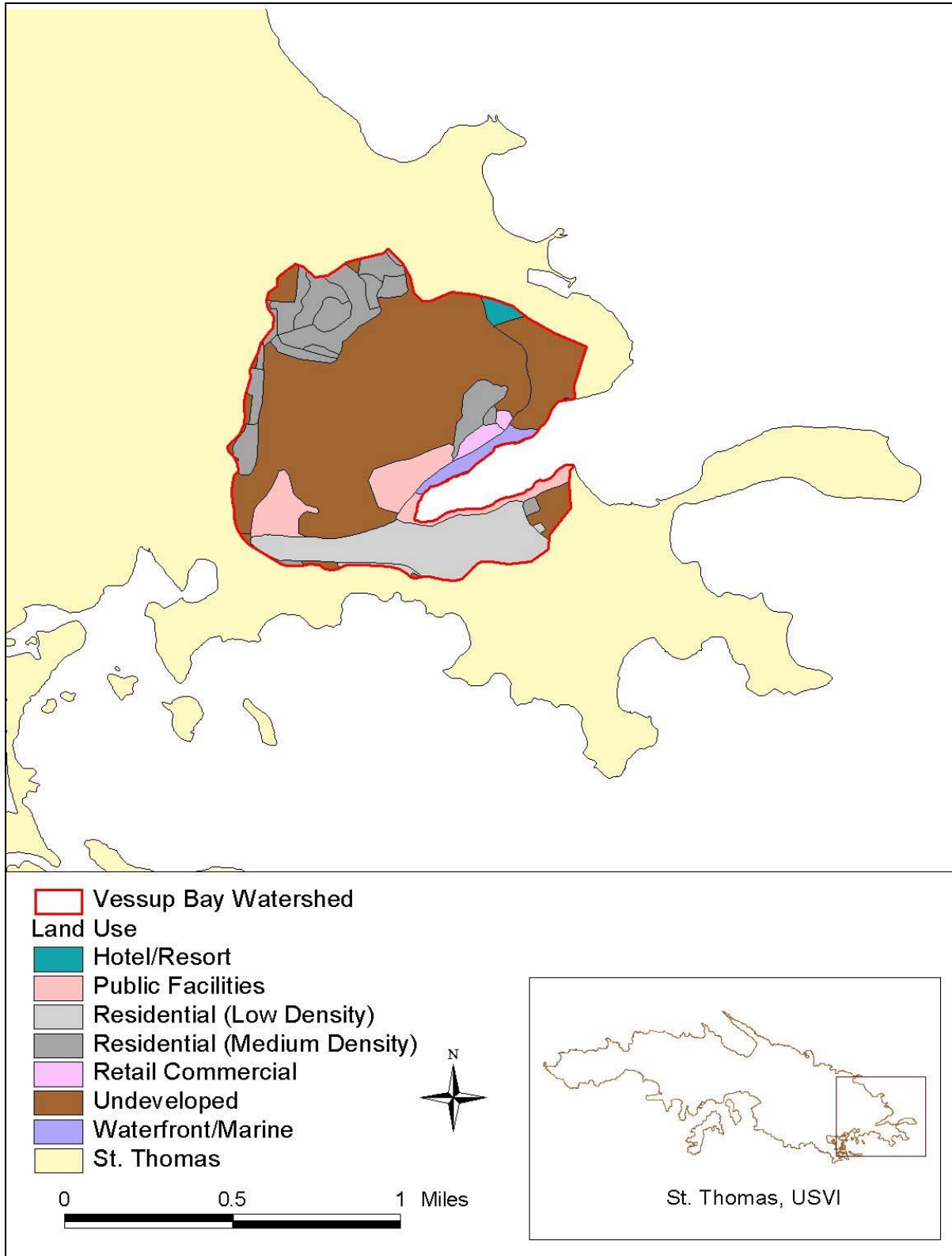


Figure 4-1. Landuse Distribution in the Vessup Bay watershed.

4.1.5 Temporal Disaggregation of Load Estimates

For the purpose of evaluating the influence of sources on time-variable bacteria concentrations within Vessup Bay, a temporal disaggregation of the loading estimates was conducted. This disaggregation was only conducted for the general land surface loading and septic loading categories. Marina loading and Vessup Bay WWTP contributions were assumed to be constant. The land surface loads were disaggregated to represent variability due to rainfall events and seasonal trends. During dry periods with no rainfall, no transport vehicle is available to introduce bacteria to surface waters. Instead, bacteria remains on the land surface until rainfall-driven overland flow occurs and transports the load to an adjacent stream. Therefore, the majority of loading from this source occurs during and just following rainfall events. Similarly, loading rates from failing septic systems in the region are dependent on wet conditions for transport to surface waters (Aaron Hutchins, DPNR; Personal Communication 2004). Septic leach fields and failed septic containment systems are exposed to infiltrating precipitation, and they discharge bacteria loads, when moisture levels in vadose and groundwater layers are sufficient for surface or subsurface transport. The majority of loading from this source therefore also occurs during and just following rainfall events.

To convert the load estimates described previously to daily-variable loading rates, observed flow regimes on St. Thomas were obtained. The USGS maintains a streamflow station at Turpentine Run at Mt. Zion (USGS 50274000), and this gage monitored flow at that location from October 1st, 1992 to September 30th, 2004. Flow at the Turpentine Run at Mt. Zion gage from 1/1/1998 – 9/30/2004 is shown in Figure 4-2. streamflow data at this gage was assumed to be representative of streams contributing to Vessup Bay, and thus area-weighting the flow measured at this gage represents the net flow to the bay.

A flow accumulation curve was first developed based on the observed streamflow data (Figure 4-3). The accumulation curve displays the percentage of the total 1/1/1998-9/30/2004 volume discharged versus date. Steep increases in percentage indicate high flows, while gradual increases in percentage indicate relatively low flows. Figure 4-4 displays the percentage of the total 1/1/1998-9/30/2004 flow discharged on a daily basis. These percentages were subsequently applied to the loading rates from the land surface and septic failure sources described in the previous section.

The daily loading rates for land surface sources ($1.47\text{E}+11$ fecal coliforms/day) and septic leakage sources ($1.36\text{E}+8$ fecal coliforms/day) were multiplied by the total number of days from 1/1/1998-9/30/2004 to obtain a total loading rate for that period of time. The daily percentages shown in Figure 4-4 were applied to this total load to obtain variable daily loading estimates. Total daily loading rates from all sources of fecal coliform bacteria are shown in Figure 4-5.

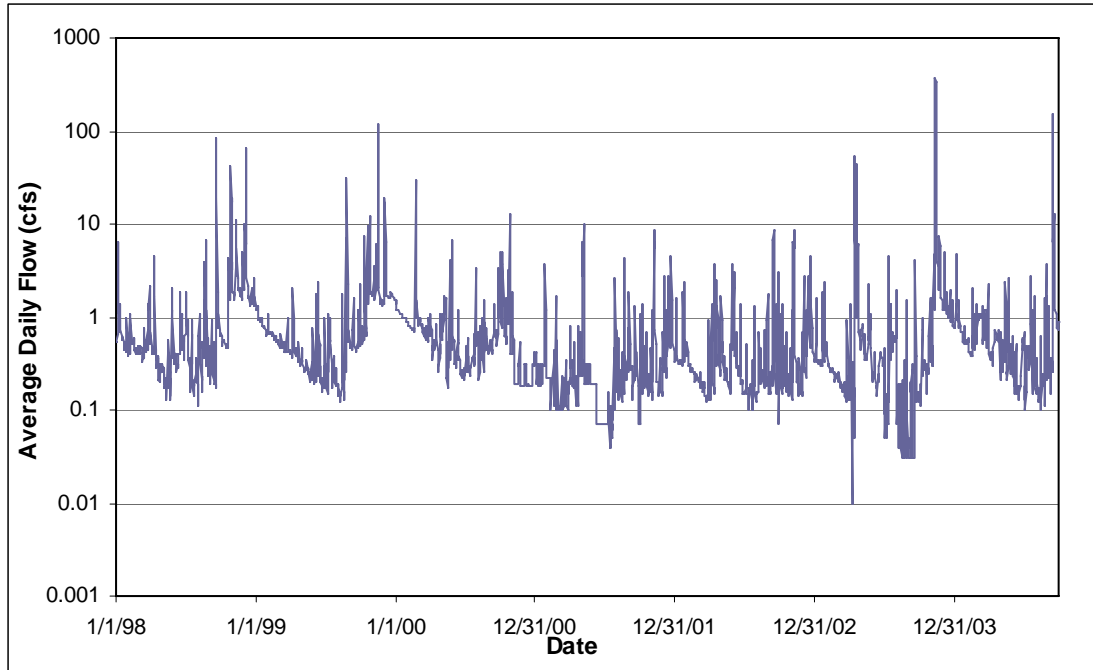


Figure 4-2. Streamflow at USGS Gage 50274000, 1/1/1998 - 9/30/2004.

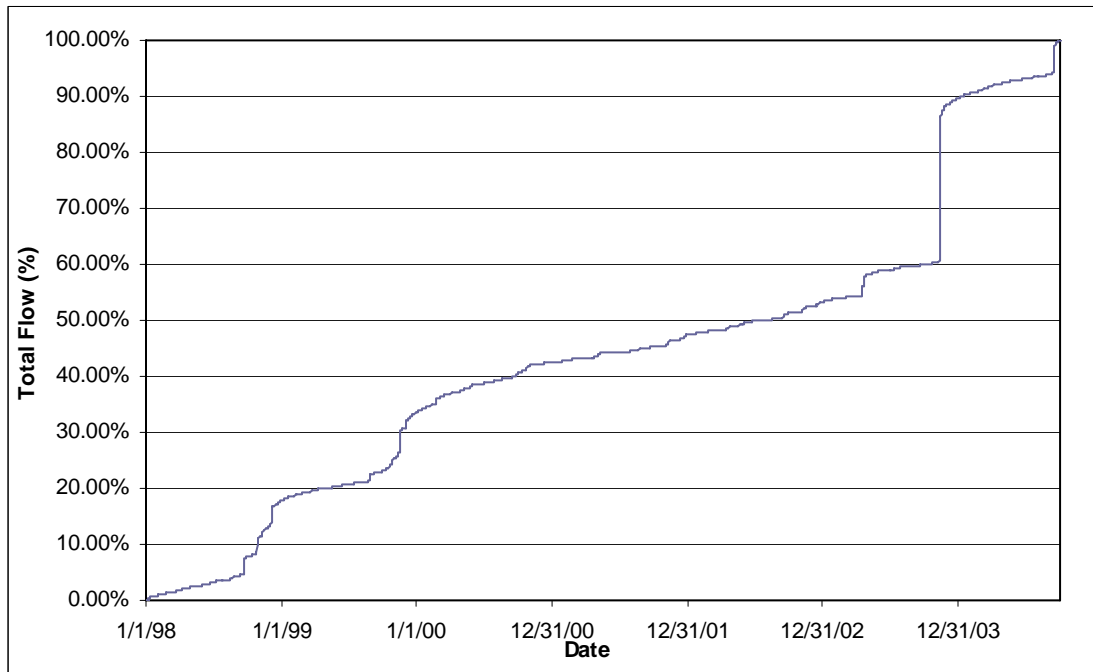


Figure 4-3. Streamflow Accumulation Curve for USGS Gage 50274000, 1/1/1998 - 9/30/2004.

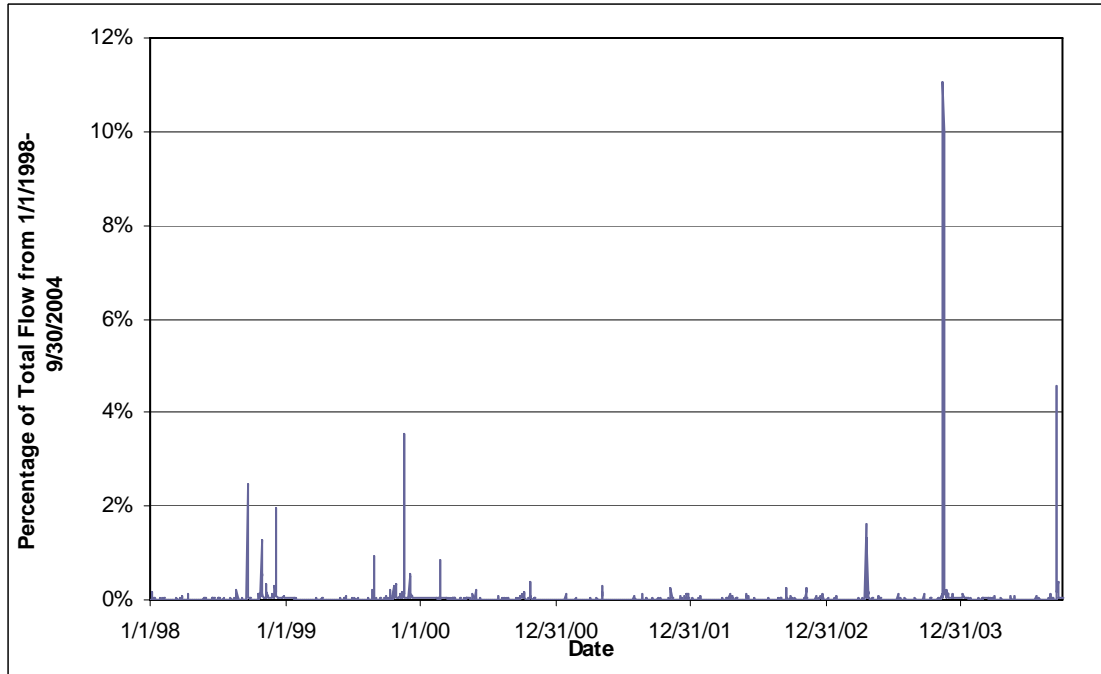


Figure 4-4. Daily Percentage of Total 1/1/1998 - 9/30/2004 Flow for USGS Gage 50274000.

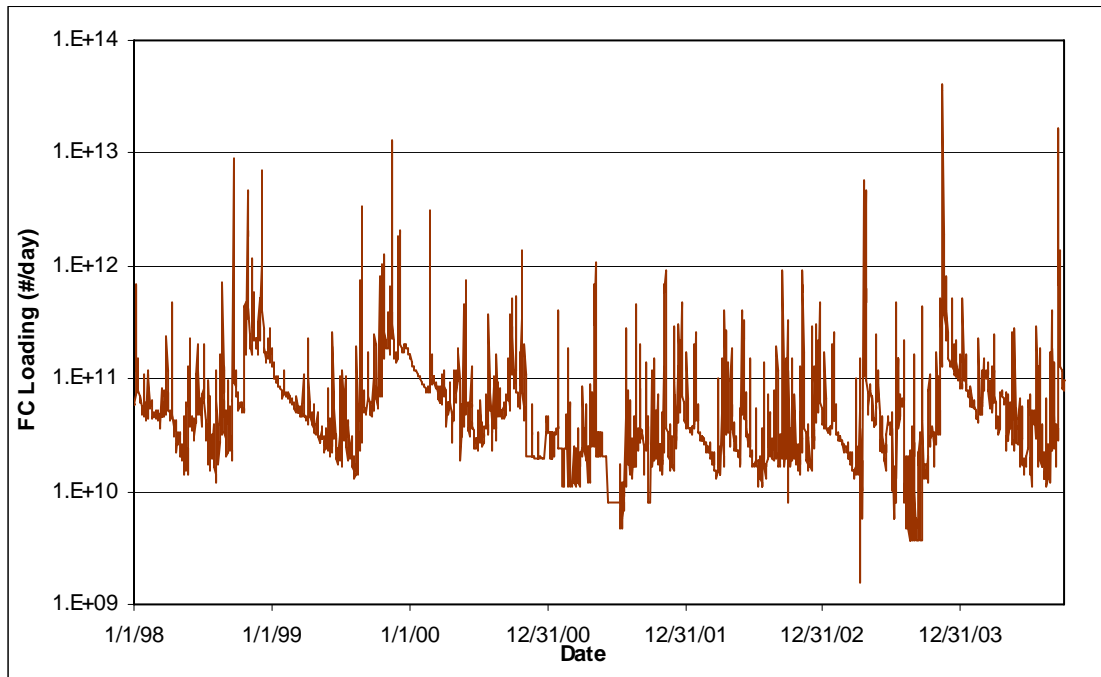


Figure 4-5. Estimated Loading of Total Fecal Coliform Bacteria to Vessup Bay, 1/1/1998-9/30/2004.

4.2 Tidal Prism Model

The daily fecal coliform bacteria loads representing all source contributions were introduced to a tidal prism model to predict fecal coliform bacteria levels over time within Vessup Bay. The concept of the tidal prism model is shown in Figure 4-6. In Vessup Bay, the ebb and flood of the tide move water between locations exchanging and mixing with other water. Apart from this, the amount of freshwater discharge into the embayment is also one of the dominant influences on the transport of fecal coliform. The tidal prism method of estimating in-bay fecal coliform concentrations uses the volume of the waterbody and adjusts for tidal flushing, freshwater inflow and bacteria load, and bacteria decay in order to establish the existing conditions in the estuary. The conceptual and mathematical components of the tidal prism model are further described in Appendix B.

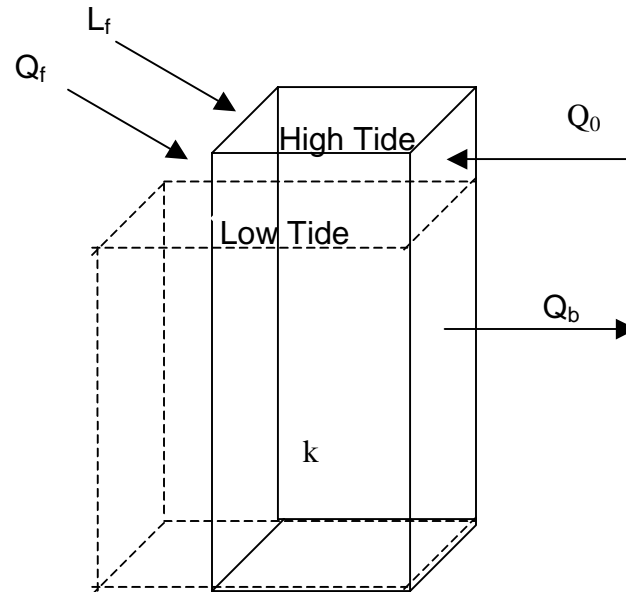


Figure 4-6. Tidal Prism Model Concept.

4.3 Assumptions and Limitations

Some of the major underlying assumptions for this analysis include the following:

- Observed streamflow data at Turpentine Run at Mt. Zion gage (USGS 50274000) was assumed to be representative of streams contributing to the bay, and area-weighting the flow measured at this gage represents the net flow to the bay.
- The watersheds delineated were based on topographic data and available stream and channel coverages. Data regarding flow diversions to or from other watersheds were not available and therefore not considered in the analysis.
- Regeneration of fecal coliform bacteria in the bay is not a significant source.
- The rate of decay for fecal coliform bacteria (0.8 1/day) does not vary seasonally or based on meteorological conditions. The decay rate was applied to the tidal prism model component only.
- When estimating the watershed contributions, a decay rate was not applied to bacteria loads from the land surface.
- 10% of bacteria discharged to watershed streams were assumed to reach the bay to address decay and attenuation.
- Point sources and marina contributions were not assigned a decay rate prior to introduction to the tidal prism model
- Bacteria loadings from point sources and marina discharges are time-constant and equivalent for storms of any size, and thus do not consider antecedent conditions.
- Bacteria loadings from the land surface and septic systems, although temporally disaggregated, may not represent the full range of possible bacteria concentrations. The disaggregation procedure inherently applies equal weighting to low flow and high flow conditions (thus the first-flush phenomenon and antecedent conditions are not considered).
- Bacteria concentrations estimated by the tidal prism model assume the volume is fully-mixed, and that bacteria concentrations are horizontally and vertically-averaged.

A number of limitations were inherent in the analytical process because of the approach selected. These limitations are identified below. Although these limitations are present, the approach followed successfully resulted in TMDL identification. If additional data are collected for the Vessup Bay watershed, many of these limitations can be addressed.

- Watershed loading estimates for fecal coliform bacteria monitoring data could not be verified due to a lack of monitoring data upstream of the Bay. However, the watershed loading estimates (see Section 4.1) were applied to the Tidal Prism model of the bay, which produced results within the range of quarterly ambient monitoring data. Based on the uncertainty related to estimating watershed loading, a calibration or validation effort was not justified.
- The comparison between ambient data and Tidal Prism results was rudimentary in nature, based on the infrequency of data collection and resulting simplistic methodology.

- High in-bay bacteria concentrations are assumed to occur under high flow conditions.
- Other than land use type area data, annual rainfall quantities, and stream length, default parameter values were used in the WTM model (see Section 4.1.2) to represent land surface contributions of bacteria.
- Population estimates for the watershed were calculated based on 2000 Census data for St. Thomas.
- The population in the watershed was an area-weighted estimate based on 2000 census data. Based on the ratio of sewered to unsewered households on St. Thomas, it was estimated that approximately 39.6% of the population is serviced by on-site septic systems. 10% Of the discharged load was assumed reach the assessment unit (bay itself) on a daily basis. This calculation assumed a 10% failure rate (Mangrove Lagoon/ Benner Bay BOD TMDL (2003)). It also assumes 70 gallons of septic discharge/person/day at a concentration of 10,000 CFU/100mL (Horsley and Witten, 1996).
- The bacteria load from inappropriate and illicit wastewater discharge in marinas and mooring locations was estimated based on a 2002 DPNR survey of the number of slips and mooring permits for boats, as described in the U.S. Virgin Islands Clean Vessel Act Program Implementation Plan.
- Discharge monitoring data for the Vessup Bay WWTP are not available, thus an estimate of bacteria contributions based on permitted discharge limits (see Section 2.3.1) was applied.
- Representation of the point source and illicit marina discharges as time-constant source loadings reduces the sensitivity of the TMDL to low-flow impairment in bays, which are subject to tidal flushing.

5 TMDL CALCULATION AND ALLOCATIONS

A TMDL for a given pollutant and waterbody is comprised of the sum of individual wasteload allocations (WLAs) for point sources and load allocations (LAs) for both nonpoint sources and natural background levels. In addition, the TMDL must include a margin of safety (MOS), either implicitly or explicitly, to account for the uncertainty in the relationship between pollutant loads and the quality of the receiving waterbody. Conceptually, this definition is represented by the equation:

$$\text{TMDL} = \sum \text{WLAs} + \sum \text{LAs} + \text{MOS}$$

The TMDL is the total amount of pollutant that can be assimilated by the receiving waterbody while still achieving the TMDL target. In TMDL development, allowable loadings from pollutant sources that cumulatively amount to no more than the TMDL must be established; this provides the basis to establish water quality-based controls. TMDLs can be expressed on a mass loading basis (e.g., pounds of DO per year) or as a concentration in accordance with 40 CFR 130.2(i).

5.1 Numeric Target for Fecal Coliform Bacteria

The TMDL target for Vessup Bay is 63 fecal coliforms per 100mL or less for the 90th percentile concentration. The target concentration of 63 fecal coliforms per 100mL was selected based on the water quality criteria discussed in Section 2.2, minus a 10% explicit MOS. A distribution of tidal prism bacteria concentration results, based on watershed and in-bay loading (see Section 4.2), was created and is shown in Figure 5-1 for the existing and TMDL scenarios. The conceptual model of the tidal prism is described in section 4.2, and the algorithms used in the tidal prism model are explained in Appendix B. The lowest 90% (90th percentile) of the population of in-bay concentrations was not allowed to exceed 63 fecal coliforms per 100mL for the TMDL condition. This 90th percentile threshold corresponds to the USVI assessment methodology for Class B waters, which states that waters are supporting beneficial uses if 10% or less of bacteria samples exceed 70 fecal coliforms per 100mL. Therefore, the 90th percentile concentration is the critical condition, as described in Section 3.2.

Compliance with the TMDL target was evaluated based on a percentile distribution of the tidal prism model results (as shown in Figure 5-1). The 90th percentile concentration for the existing condition is 66.1 fecal coliforms per 100mL. A 7.02% reduction in bacteria loading met the target of 63 fecal coliforms per 100mL in the bay. Therefore, this is the reduction required to meet the TMDL. The allocations for the bacteria sources are discussed below.

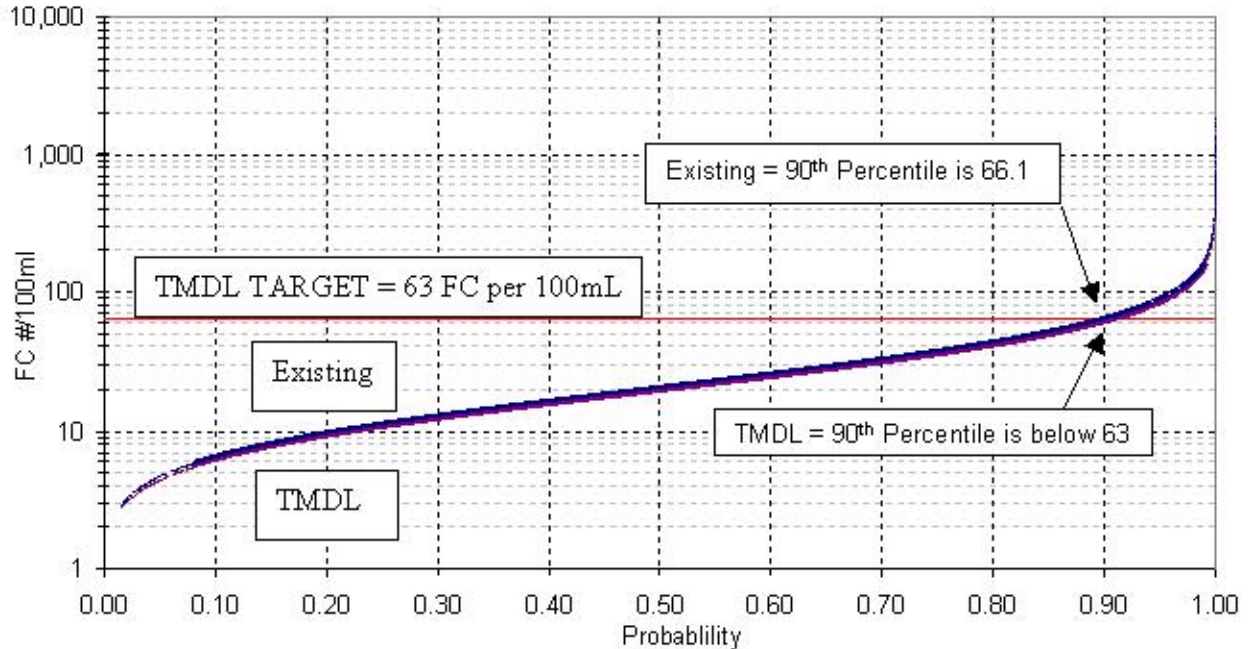


Figure 5-1. TMDL Calculation Methodology based on Tidal Prism Model Reduction Scenarios.

5.2 Wasteload Allocations

Federal regulations (40 CFR 130.7) require TMDLs to include individual WLAs for each point source. There is one permitted point source in the Vessup Bay watershed (Vessup Bay WWTP). The maximum permitted load identified by TPDES was used to estimate loading. Based on the current permit, no further reductions from this source are required (See Table 5-1).

5.3 Load Allocations

Based on the analysis performed, the primary nonpoint source contributions to Vessup Bay are from the land surface and failing septic systems. Therefore, the TMDL requires a 7% reduction in bacteria loading from land surface loads and a 50% reduction from failing septic system loads. Illicit discharges from vessels docked at marinas, although less significant with respect to bacteria levels, were reduced to zero based on the fact that they are illicit in nature. Source-based reductions were arrived at through an iterative process of examining bacteria reduction possibilities by varying bacteria loads from each source to the bay and ensuring that the TMDL target was being met.

5.4 Margin of Safety

There are two methods for incorporating the MOS (USEPA, 1991):

- Implicitly incorporate the MOS using conservative model assumptions to develop allocations.
- Explicitly specify a portion of the total TMDL as the MOS and use the remainder for allocations.

For Vessup Bay, an implicit MOS was incorporated in several ways. Throughout the TMDL development process, conservative assumptions were made to address the implicit component of the MOS. In addition, an explicit 10% MOS was included in the fecal coliform bacteria concentration target. A TMDL target of 63 fecal coliforms per 100mL was selected based on the water quality standards discussed previously (70 fecal coliforms per 100mL; Section 2.2), minus a 10% explicit MOS.

5.5 TMDL

The TMDL components are presented by Assessment Unit in Table 5-1. Each source of bacteria (contributing to that Assessment Unit specifically) is identified for both existing and TMDL conditions. The components of existing land surface contributions in Table 5-1 were calculated using the WTM model and are shown in Table 4-1. Failing septic system contribution calculations are shown in Table 4-2, and marina contributions are calculated in Table 4-3. Consideration of seasonality is a requirement for the TMDL and was considered in a number of ways. Streamflow data from an active USGS station was used to estimate time-variable bacteria loading and subsequent in-bay response. Observed streamflow at the gage varies by season as described previously. As supported by the discussion in Section 3-2 and observed data shown in Table 3-2 and Figure 3-4, high in-bay bacteria concentrations are assumed to occur under high flow conditions. Therefore, based on the methodology used to estimate watershed loadings, seasonal loading of bacteria to the bay was considered in the TMDL.

Table 5-1. Summary of the Vessup Bay TMDL.

Condition		Units	VESSUP BAY AU-STT- 23	
Existing (1998- 2002)	Nonpoint Sources	Land Surface Washoff Contributions	(#/day Fecal Coliform)¹	1.47E+11
		Failing Septic Contributions	(#/day Fecal Coliform)²	1.36E+08
		Marina Contributions	(#/day Fecal Coliform)³	2.09E+08
	Permitted Point Source Contributions	Vessup Bay WWTP (VI0020133)	(#/day Fecal Coliform)⁴	2.62E+08
	Total existing loads		(#/day Fecal Coliform)	1.47E+11
TMDL	LA	Land Surface Washoff Contributions	(#/day Fecal Coliform)⁵	1.36E+11
		Failing Septic Contributions	(#/day Fecal Coliform)⁶	6.79E+07
		Marina Contributions	(#/day Fecal Coliform)⁷	2.09E+08
	WLA	Vessup Bay WWTP (VI0020133)	(#/day Fecal Coliform)⁴	2.62E+08
	MOS	Margin of Safety	(#/day Fecal Coliform)⁸	-
	TMDL	Total Maximum Daily Load	(#/day Fecal Coliform)	1.37E+11

Note:

¹ Land Surface contributions calculated based on information shown in Table 4-1.

² Failing Septic contributions calculated based on information shown in Table 4-2.

³ Illicit marina contributions calculated based on information shown in Table 4-3.

⁴ Permitted point source contributions calculated based on information shown in Table 2-2.

⁵ Based on a 7% reduction in bacteria loading from land surface contributions.

⁶ Based on a 50% reduction in bacteria loading from failing septic systems.

⁷ In anticipation of future "no-discharge" legislation for Vessup Bay

⁸ The Margin of Safety (MOS) was not applied as a loading rate in this TMDL. Instead, a lower fecal coliform bacteria concentration target of 63 fecal coliforms per 100mL was used as an explicit MOS.

6 MONITORING RECOMMENDATIONS

Seasonal variations including temperature, precipitation, wind direction and speed, water and air temperature, currents, and seasonal population fluctuations most likely affect the water quality within this system. Sample locations should be predetermined based on several factors, including location relative to critical land uses, stream discharge locations, and marina locations. Additional sample locations should be selected to capture the general ambient water quality and flow conditions within the water bodies. Most importantly, sample locations should be consistently adhered to for all sampling events. If sample locations are too loosely defined, it becomes increasingly difficult to accurately interpret the resulting data and the sampling effectiveness decreases significantly. Ideally, all sampling will be implemented on a monthly basis. This will provide a consistent and comprehensive data set that can be effectively analyzed and utilized in a transient model. To better characterize the impact of rainfall-driven sources, stormwater sampling should also be conducted during storms of varying magnitude. Sampling should be conducted within the bay itself and at locations throughout the watershed.

Another recommendation is to monitor pumpout facilities at the marinas in the region. The availability of a pumpout log would allow this significant source of bacteria to be better defined, and provide better information regarding daily, monthly, and seasonal marina usage.

In order to meet the goals of the monitoring plan, as discussed at the beginning of this section, the suite of parameters to be sampled is listed below. Following is a recommended list of the parameters to be monitored within Vessup Bay. Ideally, these parameters should be sampled at various locations and multiple depths when applicable, and at a maximum time interval of monthly:

- Fecal Coliform Bacteria
- Water Temperature
- Turbidity

These parameters would allow for further identification of bacteria sources and support critical condition assessment. A sampling plan including these parameters should provide a baseline condition to be used in BMP efficiency assessments in the Vessup Bay system.

7 IMPLEMENTATION AND MANAGEMENT

The monitoring recommendations in Section 6 should be performed in conjunction with management practices designed and implemented to reduce source loadings of fecal coliform bacteria. According to current knowledge, fecal coliform is an important contributor to the impairment of Vessup Bay. A reduction of bacteria loading rates would provide great improvement in water quality.

Implementation and management of this TMDL should occur in four interrelated areas:

- infrastructure provision – the provision of infrastructure designed to intercept and ‘treat’ stormwater and sewage effluent;
- policy and regulation – the creation of law and regulations designed to control the discharge of bacteria from sources;
- design and practice – the use of Best Management Practices (BMPs) designed to attenuate source loadings to impaired waterbodies;
- education – the spread of knowledge about the sources, pathways and sinks of bacteria designed to change behavior.

Work in these four areas will greatly impact source loadings to Vessup Bay. The following four sections give examples of the types of actions that might be taken to reduce source loadings.

7.1 Infrastructure Provision

One of the largest sources of fecal bacteria to Vessup Bay is stormwater. Stormwater runoff from residential, commercial, and industrial areas often contains levels of bacteria and other harmful (pathogenic) organisms (viruses, parasites) that exceed public health standards for water-contact recreation or seafood consumption (UVI, 2002). These elevated bacteria levels increase the risk to public health and detrimentally affect coastal ecosystems. The increased risk to public health often leads to the closing of beaches, whose water exceeds public health standards, to recreational use. Elevated bacteria levels can result in contaminated fish and shellfish.

One form of infrastructure provision is the infiltration trench. Infiltration trenches can potentially reduce stormwater runoff so that hydrologic conditions are close to predevelopment conditions. Trenches designed to infiltrate all incoming water into surrounding soil can effectively reduce peak discharge rates associated with the design storm (the size of storm a given practice is designed to handle). However, for both physical and economic reasons, it is not always practical to design trenches for very large or infrequent storms. In this case, trenches designed to infiltrate part of the runoff into the

surrounding soil and collect the rest in a perforated underdrain at the bottom of the trench and direct it to a central outlet, are more appropriate. Trenches can also reduce the increases in post-development runoff volume that are produced by small or medium-sized storms. The effectiveness of a trench in reducing stormwater runoff volumes is a function of the infiltration capacity of the surrounding soil.

Infiltration trenches are not intended to remove sediment. They are designed to remove fine particles and soluble pollutants by filtration through the trench to the surrounding soil. Pollutant removal in a trench can be enhanced by increasing the surface area of the trench bottom (i.e., make the trench shallow and broad rather than narrow and deep). This will provide more area through which infiltration to surrounding soil can occur. The greatest reduction of nutrients, metals, and bacteria will occur in soils that have higher clay contents and/or organic matter, and the least reduction will occur in sandy soils. Unfortunately, soils that maximize pollutant absorption also tend to have very low infiltration rates and are most prone to blockage. Because of this it is important that large particles are removed from stormwater runoff (by a filter strip or other practice) before it enters the trench area.

Another important source of fecal coliform bacteria is sewage effluent. Sources of such effluent are malfunctioning septic systems and other decentralized wastewater treatment systems as well as poorly maintained sewer pipes. The thin soil zone, usually less than 2 feet thick, is not capable of filtering the effluent wastes (Veve et al, 1996). The vast majority of soils in the Virgin Islands are not conducive to proper septic system functioning (USDA, 2002), specifically for conventional subsurface soil absorption fields (USVI, 2004). The effluent in these situations can either escape to the surface or enter the open joints and fractures of the bedrock and, subsequently, the ground-water reservoir. If soil absorption cannot be utilized, sewage effluent also may be safely disposed of by evapo-transpiration utilizing the constructed wetland system.

Wastewater may also be disposed of into surface waters using more complex systems. Although potentially costly, new sewer infrastructure should be put in place where economically feasible and where not feasible alternatives to traditional septic systems should be explored and implemented to the greatest extent possible. The installation of new septic systems should not occur or occur only on those soils deemed adequate for septic installation.

7.2 Policy and Regulation

Along with infrastructure provision, policy and regulation can reduce source loadings of fecal coliform bacteria. An example is pet waste. The presence of pet waste in stormwater runoff has a number of implications for urban stream water quality with perhaps the greatest impact from fecal bacteria. Animal waste collection programs use awareness and education, signs, and pet waste control ordinances to alert residents to the proper disposal techniques for pet droppings. In some parts of the country, the concept of parks or portions of parks established specifically for urban dog owners has gained in popularity. With provisions for proper disposal of dog feces and siting and design to

address stormwater runoff, these parks may represent another option for protecting local water quality (SMRC, undated).

Another example is fecal coliform introduction by boats. These loads may be reduced by implementing and enforcing a No Discharge Zone in the entire Bay (not just the Marina). Along with this designation, pumpout facilities would be maintained to provide an alternative to illicit discharges of vessel waste. Logs for these facilities must be kept to identify usage and quantities pumped.

7.3 Design and Practice

As indicated in Table 4-1, the Vessup Bay watershed is predominantly urban land use types. There are number of design practices that can capture and filter bacteria suspended in stormwater. Table 7-1 provides the basic bacteria removal capability for the most common stormwater management practices and design measures. Any implementation of these practices will entail fine-scale studies of the watershed to determine proper siting. In addition to this, monitoring in accordance with the recommendation outlined in Section 6 will be necessary to verify effectiveness.

Table 7-1. Urban Best Management Practice Median Pollutant Removal Efficiency (New York State Department of Environmental Conservation, 2001)

Best Management Practice Type	Reported Fecal Coliform Median Removal Efficiency (%)
Stormwater Wet Ponds	70
Stormwater Wetlands	78
Filtering Practices	37
Infiltration Practices	90
Water Quality Swales	Net pollutant export

As shown above, there are a suite stormwater management practices and programs that have less tangible pollutant removal capability. Caraco (2002) completed a review and assessment of potential pollutant load reductions of several of these practices based on the fraction of land or population affected by the management strategy with discount factors applied for the actual implementation

7.4 Education

An overarching component of all of the above management strategies is education. The following is from the British Columbia Ministry of Environment's Water, Air and Climate Change Branch (B.C. Ministry of Environment, 1999).

Because NPS water pollution originates from the combined actions of many individual citizens and businesses, their close involvement and support in addressing NPS pollution is absolutely

essential. However, many people are not well informed about the water quality impacts that can result from certain behaviors such as pouring used oil onto the ground, or by over-applying fertilizers to their lawns and gardens. First, people must be made more aware of the environmental risks associated with these types of activities and given information on environmentally-safe alternatives. Second, the public and local authorities must be convinced that pollution prevention is far better in terms of effectiveness and cost than pollution regulation and after-the-fact clean-up.

Education is the key to long-term change in behavior. Environmental education for all ages and across all key business sectors can get at the causes of NPS water pollution. Attitudes can be shifted that produce life-long changes in individual consumption patterns and ways of doing everyday things. Communication, education, and training are the most important strategies in managing NPS water pollution.

The Ministry goes on to say that strategies should target public and private educators and trainers, school children, local elected officials, media, industrial and utility managers, resource managers, community stewardship groups, and youth organizations.

It is only through education that the necessary political and economic will can be mustered to support the other implementation and management practices listed above. Currently in the VI, public education efforts are limited and entail public displays at the agricultural and eco-fairs as well as a small pilot project aimed at public schools for the implementation of non-point source education programs.

After implementing the above controls, if the fecal coliform criteria is not met, the USVI should re-evaluate all the new data and consider establishing a new TMDL, as necessary. The TMDLs can also be re-evaluated in several years after sources have been reduced or removed and/or better data is available.

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APPENDIX A: WATER QUALITY DATA

Water Body	Station	Date	Value	units
Vessup Bay	STT-22B	9/25/98 0:00	1	#/100ml
	STT-22B	3/25/99 0:00	200	#/100ml
	STT-22B	6/29/99 0:00	44	#/100ml
	STT-22B	11/19/99 0:00	10	#/100ml
	STT-22B	12/13/99 0:00	3	#/100ml
	STT-22B	12/21/00 0:00	1	#/100ml
	STT-22B	6/14/01 0:00	46	#/100ml
	STT-22B	7/24/01 0:00	5	#/100ml
	STT-22B	12/19/01 0:00	5	#/100ml
	STT-22B	3/12/02 12:15	4	#/100ml
	STT-22B	6/21/02 10:31	0	#/100ml
	STT-22B	3/7/03 12:18	0	#/100ml
	STT-22B	6/4/03 11:15	1	#/100ml
	STT-22B	12/3/03 14:33	1	#/100ml
	STT-22B	3/10/04 0:00	0	#/100ml
	STT-22B	8/25/04 0:00	0	#/100ml

APPENDIX B: TIDAL PRISM MODEL

The tidal prism model assumes that a single control volume can represent a waterbody, and that the pollutant is well-mixed in the waterbody system.

The mass balance of water can be written as follows (Guo and Lordi, 2000):

$$\frac{dV}{dT} = (Q_0 - Q_b + Q_f) \quad (1)$$

where:

Q_0 is the quantity of water that enters the embayment on the flood tide through the ocean boundary (m^3 per tidal cycle)

Q_b is the quantity of mixed water that leaves the bay on the ebb tide that did not enter the bay on the previous flood tide (m^3 per tidal cycle)

Q_f is total freshwater input (m^3 per tidal cycle)

V is the volume of the bay (m^3)

T is the dominant tidal period (hours)

It is further assumed that Q_0 is the pure ocean water that did not flow out of the embayment on the previous ebb tide, and that Q_b is the embayment water that did not enter into the system on the previous flood tide. The mass balance for the fecal coliform can then be written as follows:

$$V \frac{dC}{dT} = Q_0 C_0 - Q_b C + L_f - kVC \quad (2)$$

where:

L_f ($Q_f \cdot C_f$) is the loading from upstream within the tidal cycle

k is the fecal coliform decay rate (or a damped parameter for the net loss of fecal coliform)

C is fecal coliform concentration in the embayment

C_0 is the fecal coliform concentration from outside the embayment

In a steady-state condition, the mass balance equations for the water can be written as follows:

$$Q_b = Q_0 + Q_f \quad (3)$$

A numerical solution for equation (2) can be developed for the fecal coliform concentration to simulate a time-variable result by substituting finite difference

approximations for the derivatives. The fecal coliform concentration in the embayment can be calculated from equation (2) as follows:

$$Q_0 C_0 - Q_b C^{i+1} + Q_f C_f - kVC^{i+1} = V \frac{C^{i+1} - C^i}{\Delta t} \quad (4)$$

$$C^{i+1} = \frac{[\Delta t/V (Q_0 C_0 + L_f) + C_i]}{[1 + \Delta t/V (Q_b + kV)]} \quad (5)$$

The daily load can be estimated based on the dominant tidal period in the area. The dominant tidal period was assumed to be approximately 12 hours. If fecal coliform concentration is in MPN/100ml, the daily load (counts day⁻¹) can be estimated as:

$$Load = Load_T \times \frac{24}{12} \times 10000 \quad (6)$$

Since Q_0 (the quantity of water that enters the embayment on the flood tide through the ocean boundary) is unknown, it was determined indirectly.

Usually Q_0 is not known and the only known quantity at the ocean boundary is the tidal range of the tidal embayment. A tidal range time series was computed for the dominant tidal period based on observed hourly data from the Charlotte Amalie, St. Thomas station (NOAA/NOS #9751639)(see Figure 3-3). From that, Q_T , the total ocean water entering the bay on the flood tide, can be calculated. Q_T can then be used to calculate Q_0 , the volume of new ocean water entering the embayment on the flood tide by using the ocean tidal exchange ratio β :

$$Q_0 = \beta \cdot Q_T \quad (7)$$

where β is the exchange ratio and Q_T is the total ocean water entering the bay on the flood tide. The numerical value of β is usually smaller than 1, and it represents the fraction of new ocean water entering the embayment.

In general, the exchange ratio values range from 0.3 to 0.7 (VDEQ, 2005, Kuo et al., 1998; Shen et al., 2002). A mean value of 0.5 was used for the exchange ratio in Vessup Bay. Once Q_0 is known, then Q_b can be calculated from equation (3).