# Watershed Characterization and Planning for Pathogen Source Reduction in the U.S. Virgin Islands

**Prepared for:**

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**Prepared by:**

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## 1.1 Introduction

Bacterial contamination of water resources poses a significant threat to the health and sustainability of human and ecological communities in the U.S. Virgin Islands (USVI). The 2010 *USVI Integrated Water Quality Monitoring and Assessment Report* (Virgin Islands Department of Planning and Natural Resources) cites pathogenic bacteria as a major pollutant of coastal water bodies and groundwater throughout the territory. One proposed source of pathogen contamination is failing onsite sewage disposal systems (OSDS), which provide a direct connection between surface/subsurface waters and insufficiently treated wastewater that may support pathogen populations. Past studies have identified OSDS failure in the USVI as a critical issue (Kimball Chase, 1994; Wernicke, 1998). This report documents the current state of knowledge of OSDS use and failure in the USVI, presents results of updated OSDS suitability and failure probability analysis, and provides recommendations for improved wastewater management.

## 1.2 Description of Study Area

The USVI are approximately 1,100 miles southeast of the continental US along the northern boundary of the Caribbean Sea. They consist of three major islands (St. Croix, St. John, and St. Thomas) and multiple smaller islands, covering a total land area of 130 square miles. The 2010 US Census placed the USVI population at 110,000. Densely populated areas include the cities of Charlotte Amalie on St. Thomas and Christiansted on St. Croix. Population density is low on St. John, though the island is currently experiencing a high rate of population growth. USVI residents are primarily employed in the public sector or by the local tourism industry (U.S.Virgin Islands Department of Labor, 2006). The HOVENSA oil refinery in south St. Croix is also a major employer of island residents. Median individual income for the territory (based on 2000 US Census data) is $26,925 per year.

USVI climate is typical of maritime tropical environments; warm and stable temperatures, steady winds, and frequent light rainfall with no sharply defined wet or dry season (U.S. Department of Agriculture, 2000). Intense rainfall events generally occur from June through November in the form of tropical depressions, storms, or hurricanes. Topography is a major factor affecting the variability of rainfall by location, with elevated areas receiving higher rainfall due to orographic lifting of warm, moist air. St. Thomas and St. John (located 40 miles north of St. Croix) are characterized by steep slopes and mountainous terrain over most of their land area, while St. Croix includes mountainous regions and broad coastal plains. Total rainfall is not sufficient to offset atmospheric demand for water or support perennial streams or rivers, creating intermittent to ephemeral flow conditions in stream channels (locally referred to as guts). High volume flows can develop during and immediately after large rain events. These events typically flush pollutants accumulated on the landscape or in the subsurface into coastal waters.

In addition to climate and topography, USVI soils play a large role in determining the characteristics of water resources throughout the islands. Soils generally have moderate near-surface permeability but are restricted in depth by a shallow layer of low permeability soil or bedrock. Dominant soil orders include Mollisols and Inceptisols, and loam or clay loam textures are common. Groundwater is present in fractured volcanic rock, limestone, and alluvial deposits (U.S. Geological Survey, 1996). Aquifers are mostly limited in extent and yield, with the largest being the Kingshill aquifer in central St. Croix. Overall, groundwater represents approximately 20% of the public water supply (other sources include desalinated water and rooftop collection systems), and contamination of aquifers by wastewater and other pollutants has been identified as a major public health threat (Virgin Islands Department of Planning and Natural Resources, 2010).

## 1.3 Conventional OSDS Suitability Analysis

Conventional OSDS are a typical method of sewage disposal in areas lacking a municipal sewer connection, as they provide a means for wastewater treatment with low installation and maintenance costs (Virgin Islands Department of Planning and Natural Resources, 2006). Conventional OSDS take advantage of the natural ability of soils to filter and remediate pollutants by discharging wastewater into the subsurface over a below-ground soil absorption (septic) field. In a properly functioning conventional OSDS, a septic tank provides solid separation pretreatment (Figure 1-1), and pollutants/pathogens present in clarified wastewater discharged to the septic field are removed as the wastewater percolates down through two to four feet of soil (Figure 1-2).

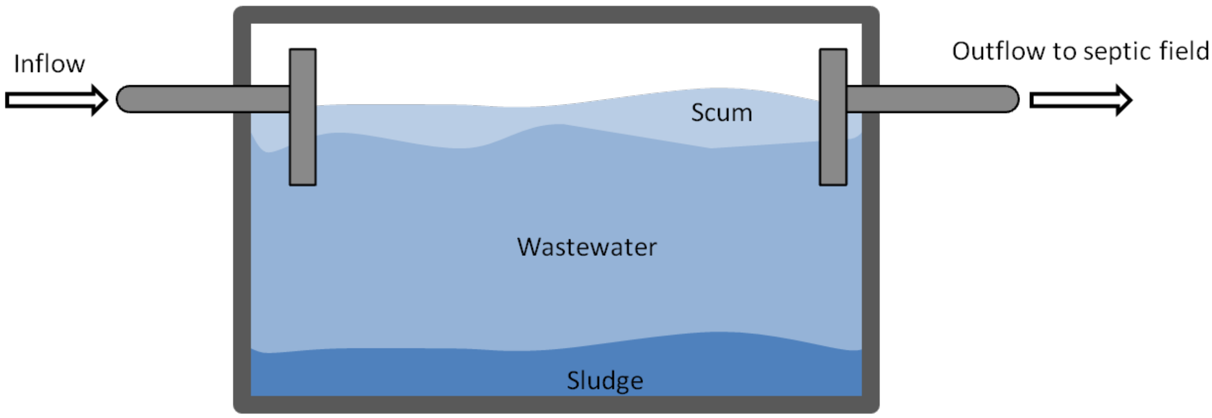



**Figure 1-1. Diagram of a typical septic tank.**

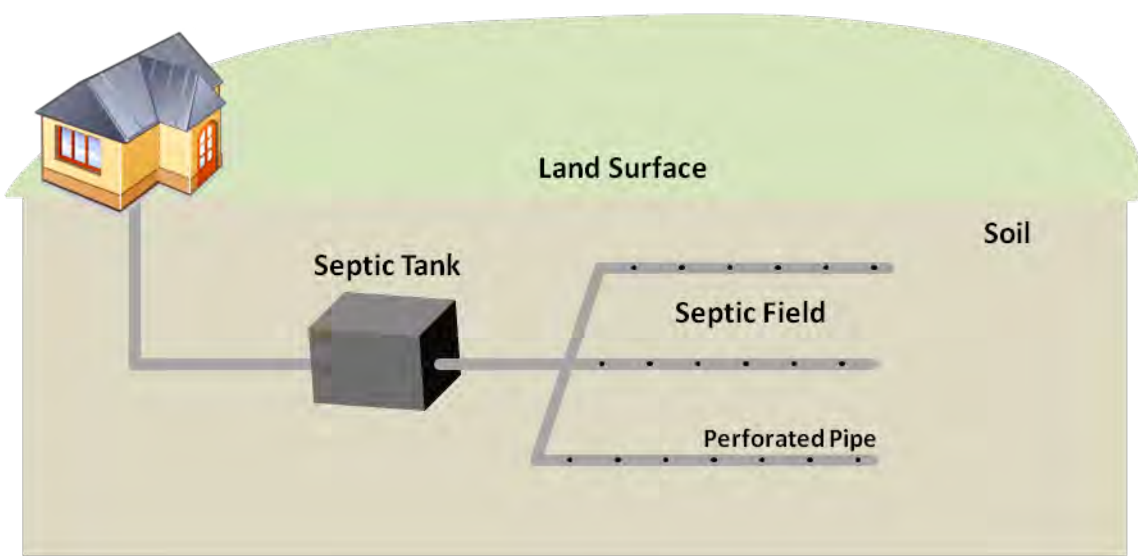



**Figure 1-2. Diagram of conventional OSDS.**

Specific soil conditions are required to ensure proper functioning of conventional OSDS, with failure prone to occur if installed in soils that drain too slowly or too quickly, shallow soils, or steeply sloped areas (Table 1-1). Trenches and beds are two types of conventional septic fields that can be used in moderately permeable and unsaturated soils. Trenches are narrower than beds, using both the bottoms and sidewalls as infiltrative surfaces, while beds are typically wider and use only the bottom of the excavation as an infiltrative surface.

Conventional OSDS have been reported to be the primary means of wastewater treatment in non-sewered areas of the USVI despite poor drainage characteristics of USVI soils (Kimball Chase, 1994). Spatial analysis of site properties outlined in (Table 1-1) was carried out to determine suitability for traditional OSDS in non-sewered USVI land parcels using high-resolution soil and topographic data. Analysis conducted at the land parcel level allows for an assessment of traditional OSDS suitability by zoning/permitted land use type. Currently, 18 zoning districts are outlined in the USVI zoning code (Virgin Islands Department of Planning and Natural Resources, 2009). Zoning districts have been condensed in this analysis into 6 zoning types: Agriculture (zoning districts A-1, A-2), Business/Commercial (zoning districts B-1, B-2, B-3, B-4, C, W-1), Industry (zoning districts I-1, I-2, W-2), Low Density Residential (zoning districts R-1, R-2), Medium/High Density Residential (zoning districts R-3, R-4, R-5), and Public (zoning district P). The current zoning type of land parcels on each major island is illustrated in Figure 1-3, (St. Croix), Figure 1-4 (St. John), and Figure 1-5 (St. Thomas). Non-sewered land parcels permitted to allow high population densities (medium/high density residential) can make significant contributions to pathogen pollution if located in areas where site conditions make conventional OSDS unsuitable.

**Table 1-1 Recommended soil and slope threshold values[1] for conventional (trench and bed) and alternative OSDS[2].**

| Method | Permeability (µm/s) | | | Shrink/Swell (%) | | | Depth to Rock (cm) | | Water Table Depth (cm) | | Slope (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **High** (>10) | **Mid** (0.1-10) | **Low** (<0.1) | **High** (6-9) | **Mid** (3-6) | **Low** (<3) | **Shallow** (<142.24) | **Deep** (>142.24) | **Shallow** (<152.4) | **Deep** (>152.4) | **<5** | **5-20** | **20-30** |
| Trench | | X | X | | X | X | | X | | X | X | X | X |
| Bed | | X | | | X | X | | X | | X | X | | |
| Chamber | | | X | | X | X | | X | | X | X | X | X |
| Mound | X | X | X | | X | X | X | X | X | X | X | X | |
| Constructed Wetland | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Sand Filter | X | X | X | | X | X | X | X | | X | X | X | X |

[1]Numeric thresholds derived from standard Natural Resource Conservation Service (NRCS) definitions (U.S. Department of Agriculture, 2010).

[2]Adapted from Table 3-2 of Virgin Islands Department of Planning and Natural Resources (2006).

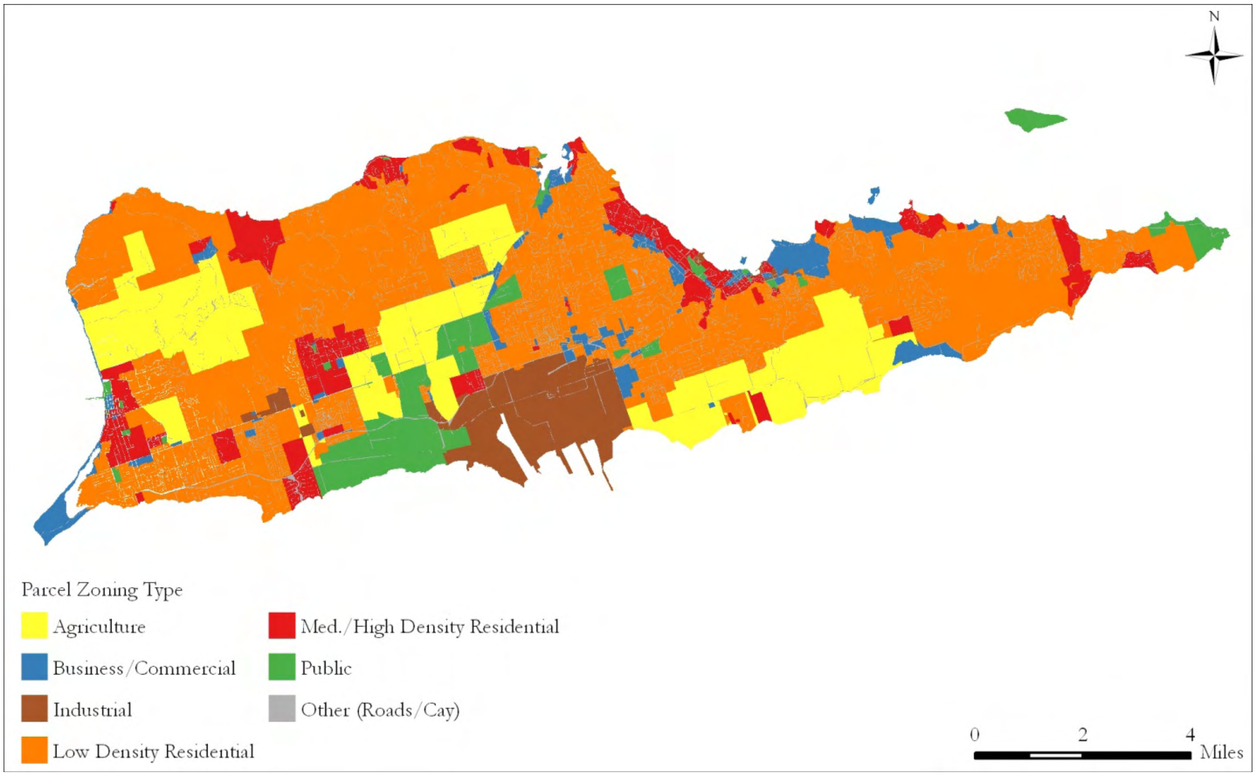



**Figure 1-3 Current zoning type of St. Croix land parcels.**

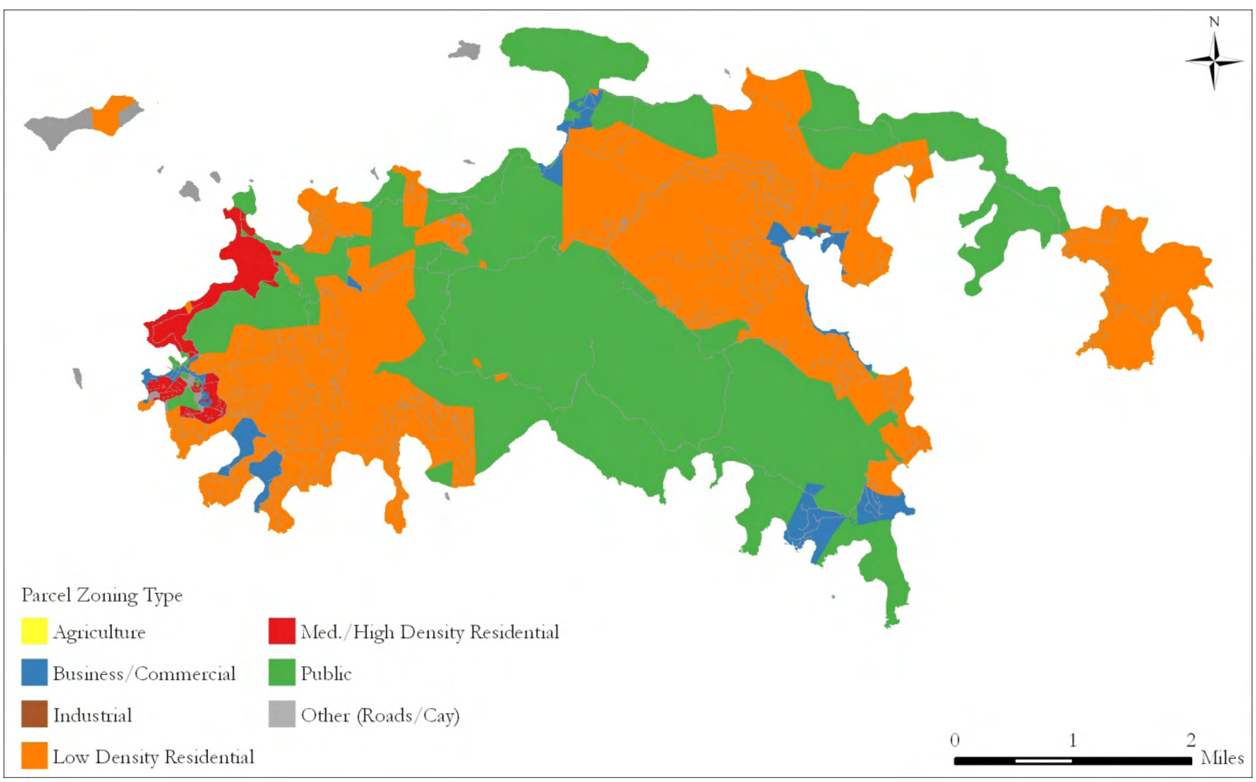



**Figure 1-4 Current zoning type of St. John land parcels.**

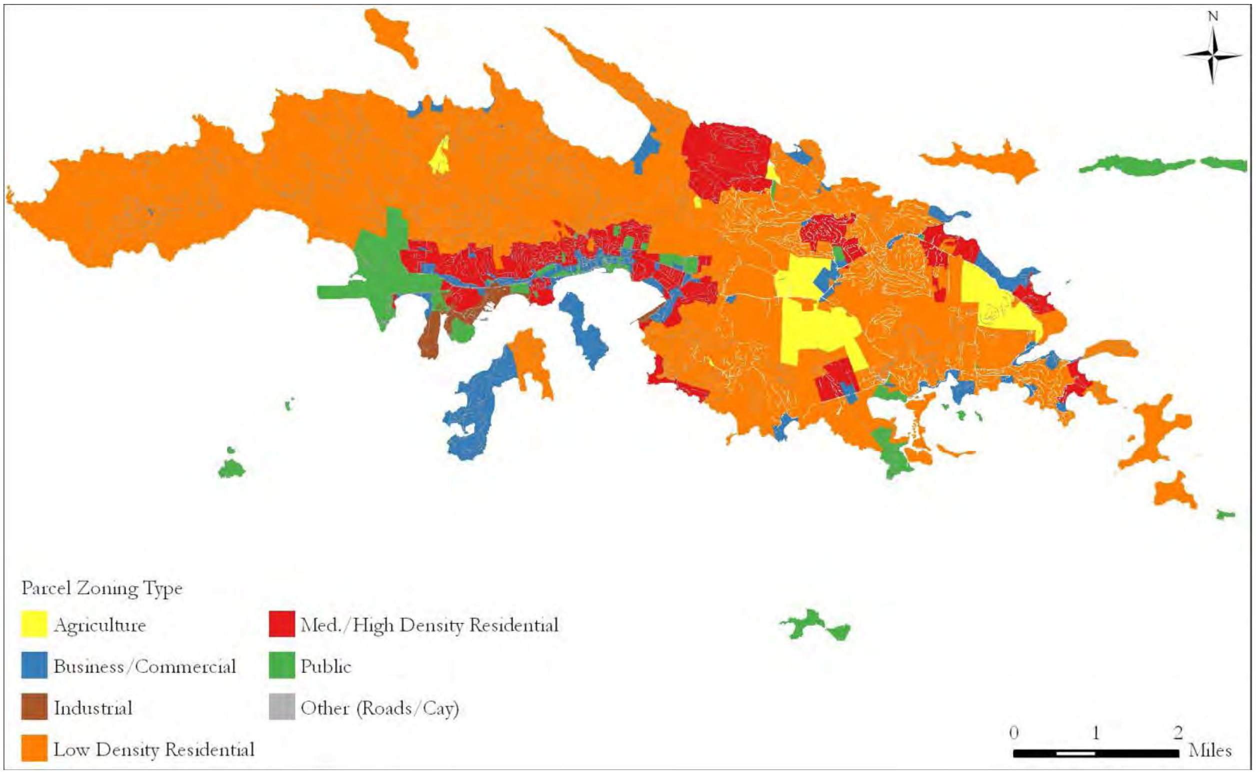



**Figure 1-5 Current zoning type of St. Thomas land parcels.**

Land parcel sanitary sewage network connections were estimated from sanitary sewage network maps provided by the USVI Waste Management Authority (WMA). Sewage network maps were made available for the island of St. Croix only. WMA sewage network maps were georeferenced, and all land parcels within 60 feet of the sewer network were assumed to contain a sewage network connection (Figure 1-6), as required by USVI law (Virgin Islands Waste Management Authority, 2007). Land parcels estimated to contain sanitary sewage network connections account for approximately 15% of the St. Croix land area (Table 1-2). Though most residential land parcels lack sewer connections, the sewer network is generally concentrated in residential areas, with 34% of the sewered land area belonging to residential zoning types. Concentration of the sanitary sewage network in residential areas eliminates the potential for OSDS failure to cause pathogen contamination where it can quickly degrade human and ecosystem health due to high population density and associated high wastewater volume generation.

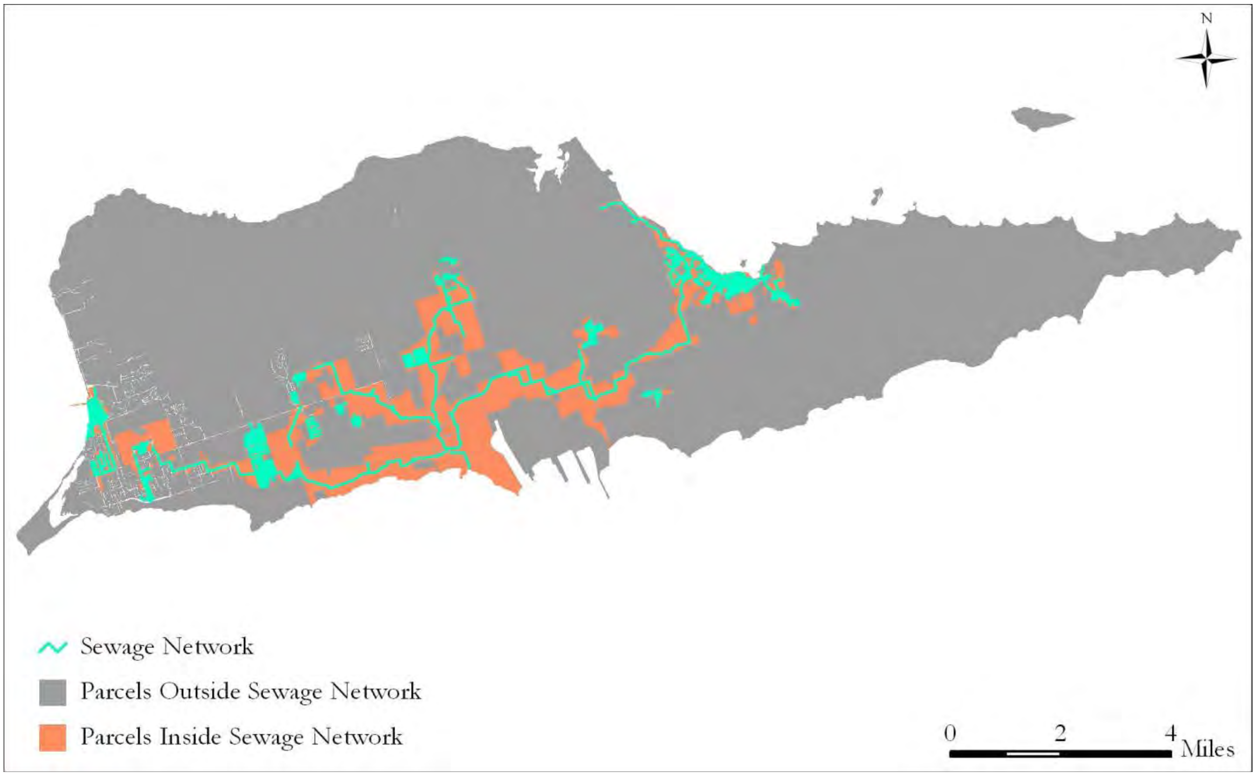



**Figure 1-6 Current extent of St. Croix sanitary sewage network.**

**Table 1-2 Zoning type of sewered and non-sewered St. Croix land parcels.**

| Zoning Type | Non-Sewered Parcels | | Sewered Parcels | |
|---|---|---|---|---|
| | Area (Acres) | % Non-Sewered Area | Area (Acres) | % Sewered Area |
| Agriculture | 8,196 | 19% | 1,391 | 18% |
| Business/Commercial | 1,800 | 4% | 361 | 5% |
| Industry | 1,654 | 4% | 1,884 | 24% |
| Residential – Low Density | 26,321 | 61% | 1,545 | 20% |
| Residential – Med./High Density | 3,483 | 8% | 1,117 | 14% |
| Public | 1,581 | 4% | 1,542 | 20% |
| **All** | 43,035 (85%) | - | 7,839 (15%) | - |

The updated suitability analysis confirmed previous reports of poor suitability of USVI soils for conventional OSDS (Kimball Chase, 1994). Figure 1-7 illustrates the suitability for conventional (trench and bed) and alternative OSDS on each major island. On the island of St. Croix, 22% of the land area was found to be suitable for conventional OSDS (Table 1-3). Conventional OSDS suitability was lower on St. John (4%) and St. Thomas (8%), and varied by zoning type (Table 1-3). On the islands of St. Croix and St. Thomas, the majority of the non-sewered land area is zoned for residential development (see Figure 1-3, Figure 1-4, and Figure 1-5). The proportion of these areas suitable for conventional OSDS is below 35% for both low and medium/high density types. On St. Croix, public lands and residential zones are approximately equal in area. Conventional OSDS are suitable for use in under 15% of these areas, with suitability as low as 3% (by area) for low density residential and public areas. The overall low proportion of the USVI land area suitable for conventional OSDS, and poor suitability in non-sewered, populated areas, suggests that traditional OSDS failure is a likely contributor to observed pathogen pollution. Suitability analysis results provide guidance to landowners as to the appropriate wastewater disposal option for their circumstances and highlight the need for alternative wastewater management strategies in unsuitable areas.

**Table 1-3 Suitability statistics for conventional OSDS (non-sewered areas).**

| Zoning Type | St. Croix | | St. John | | St. Thomas | |
|---|---|---|---|---|---|---|
| | Acres Suitable | % Suitable | Acres Suitable | % Suitable | Acres Suitable | % Suitable |
| Agriculture | 2,636 | 32% | | | 52 | 6% |
| Business/Commercial | 441 | 27% | 71 | 19% | 252 | 23% |
| Industry | 942 | 57% | <0.5 | 2% | 115 | 64% |
| Residential – Low Density | 258 | 16% | 160 | 3% | 444 | 32% |
| Residential – Med./High Density | 1,062 | 31% | 37 | 14% | 401 | 21% |
| Public | 4,028 | 15% | 176 | 3% | 296 | 2% |
| **All** | 9,367 | 22% | 444 | 4% | 1,560 | 8% |

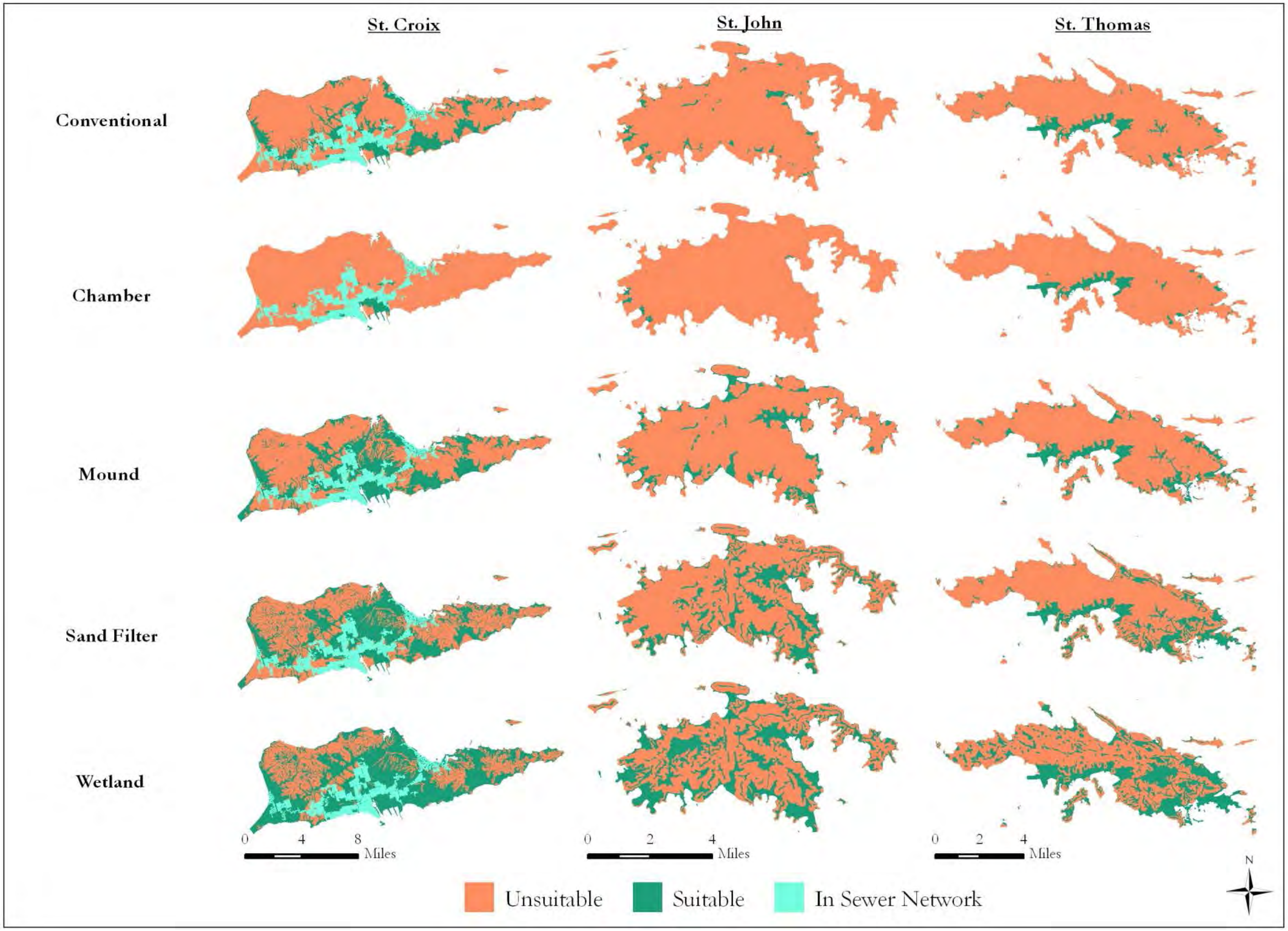



**Figure 1-7 Suitability for conventional (trench and bed) and alternative OSDS on each major island.**

## 1.4 Alternative OSDS Suitability Analysis

Alternative OSDS technologies are available for use where site conditions make conventional methods unsuitable. Treatment of wastewater to produce high quality effluent can be accomplished despite low soil permeability and shallow depth using chamber, sand filter, mound, or constructed wetland OSDS methods (see Table 1-1 for soil and slope thresholds). The chamber system (Figure 1-8) is a subsurface seepage method (similar to the conventional trench or bed system) with more widespread applicability in steeply sloped regions. In each of the remaining methods, added fill material replaces the site's natural soil as the treatment medium. In areas with a high water table or low soil permeability, a mound system can be used in which a soil absorption field is constructed over the natural land surface (Figure 1-9). A water distribution system similar to conventional systems is used to dispense wastewater effluent over permeable, unsaturated soils in the mound. Intermittent sand filters can be constructed above or below ground and require two to three feet of granular material underlain by graded gravel and collecting tile (Figure 1-9). Wastewater is applied to different segments of the sand filter at different times, allowing "resting" time for the filter to recover and avoid clogging. Sand filters provide a high level of treatment, allowing reuse of the treated wastewater for non-potable purposes if it is chlorinated. Constructed wetlands can be used under any of a diverse set of site conditions. They require a 3-chambered septic tank to allow for sufficient separation of solids. The effluent is then typically distributed to a number of sequential wetland "cells" that are constructed of concrete and an impervious liner (Figure 1-9). The wetland cells contain gravel and dirt, along with wetland vegetation. Both the substrate and the vegetation provide treatment to the wastewater.

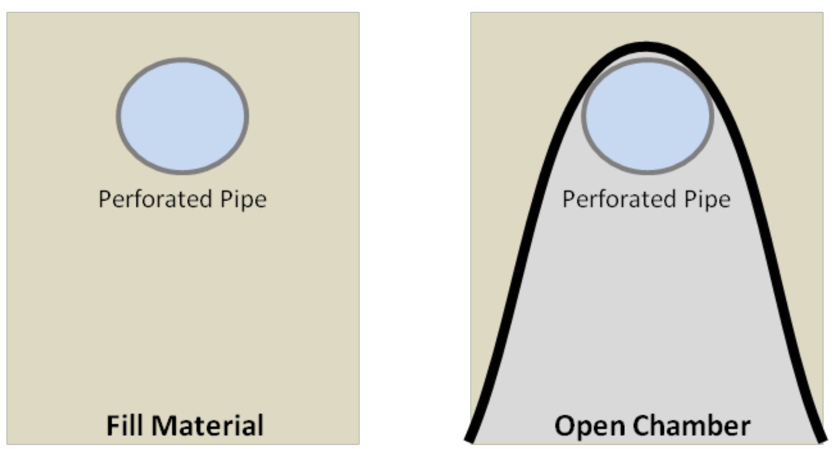



**Figure 1-8. Comparison of area surrounding septic field pipe in conventional OSDS (left) and chamber OSDS (right).**

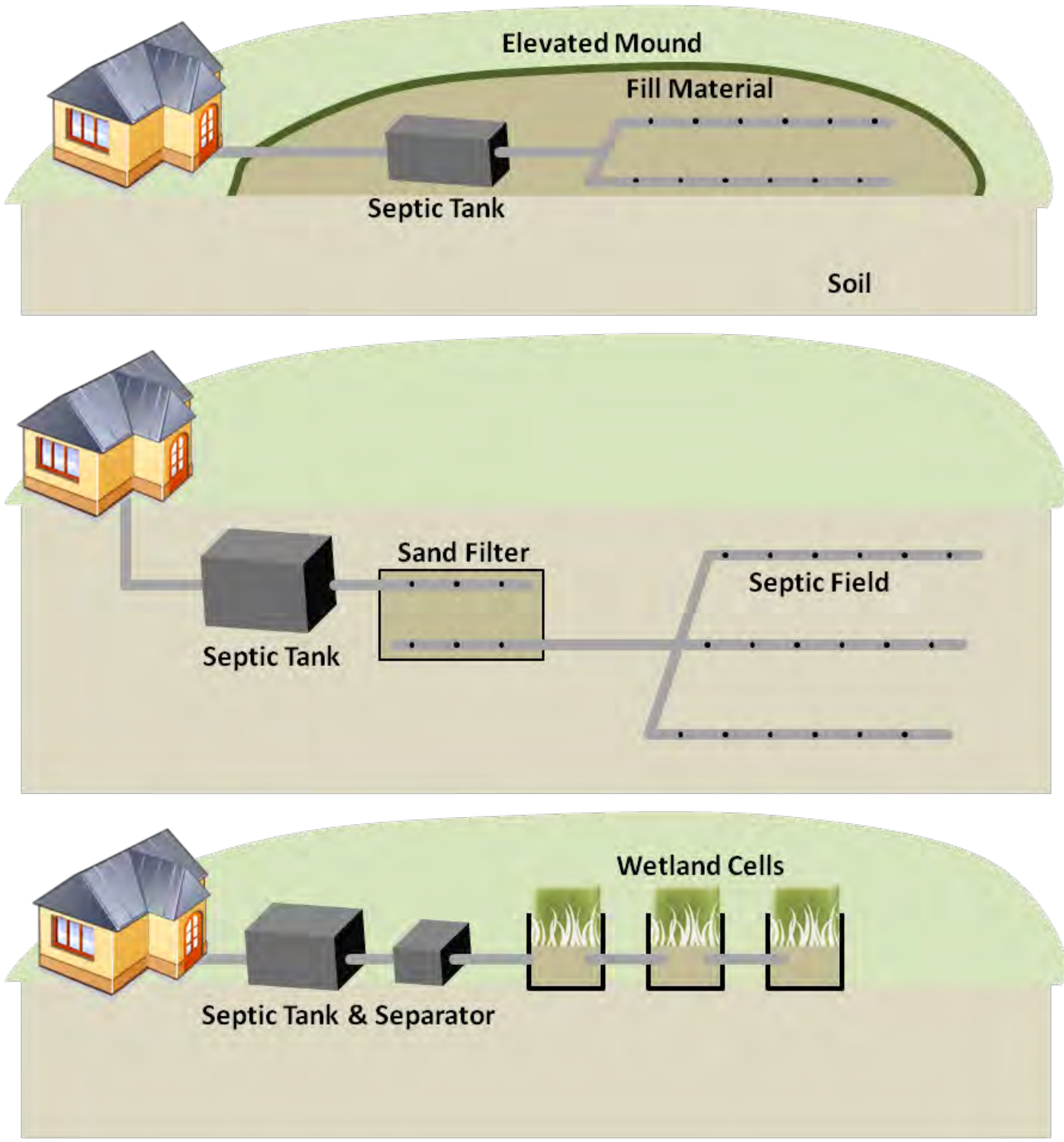



**Figure 1-9. Diagram of mound (top), sand filter (middle), and constructed wetland (bottom) OSDS.**

Spatial analysis of high resolution soils and slope data reveal higher suitability for alternative OSDS in non-sewered areas relative to conventional OSDS. Suitability varies by island, OSDS method, and zoning type (Figure 1-7, Table 1-4). The self-contained nature of the constructed wetland OSDS allows for its use in all but the most highly-sloped areas (39-61% suitability by area among major islands). A smaller land area has the conditions needed for proper function of the sand filter and mound OSDS, while the potential for implementation of the chamber OSDS is very limited due to the need for low soil permeability to adequately treat wastewater. Overall, alternative OSDS suitability is highest on St. Croix, with the constructed wetland OSDS appropriate for use across 81% of low density residential areas. Suitability for use of constructed wetland OSDS is less than 50% (by area) in low density residential areas of St. John. On all islands, more than 50% of medium to high density residential areas are suitable for installation of constructed wetland OSDS. Results of alternative OSDS suitability analysis indicate that the perceived problem of conventional OSDS failure may be partially alleviated by implementation of alternative OSDS, particularly through installation of constructed wetland OSDS in medium to high density residential areas lacking sewer connections.

**Table 1-4 Suitability statistics for constructed wetland OSDS (non-sewered areas).**

| Zoning Type | St. Croix | | St. John | | St. Thomas | |
|---|---|---|---|---|---|---|
| | Acres Suitable | % Suitable | Acres Suitable | % Suitable | Acres Suitable | % Suitable |
| Agriculture | 4,851 | 59% | | | 462 | 55% |
| Business/Commercial | 1,459 | 88% | 310 | 81% | 799 | 73% |
| Industry | 1,550 | 95% | 2 | 100% | 143 | 80% |
| Residential – Low Density | 1,280 | 81% | 1,997 | 34% | 864 | 62% |
| Residential – Med./High Density | 2,269 | 65% | 182 | 66% | 985 | 52% |
| Public | 14,804 | 56% | 2,061 | 39% | 3,992 | 30% |
| **All** | 26,214 | 61% | 4,552 | 39% | 7,246 | 39% |

## 1.5 Conventional OSDS Failure Probability Analysis

In order to help inform sewage management decisions and efforts to improve water quality, analysis was undertaken to quantify and map conventional OSDS failure probability for non-sewered USVI land parcels. Septic system failure probability was assessed through application of a soil water budget model developed by Collick *et al*. (2006). The conventional OSDS failure model estimates failure rate over time given soil and landscape properties within the land parcel, estimated dimensions of the disposal field, and meteorological conditions for the period of analysis (2007-2009). Conventional OSDS failure was defined to occur when the water table approached disposal pipes or the land surface. Under these conditions, discharge of wastewater into the subsurface septic field can create a direct surface or lateral subsurface connection with streams/guts. Soil properties considered in the conventional OSDS failure model included soil permeability, water holding capacity, the presence/depth of a soil layer which restricts the downward movement of water, and water table depth. Estimated values of these soil properties for USVI land parcels were derived from the USDA NRCS Soil Survey Geographic (SSURGO) database.

Conventional OSDS failure analysis was conducted for 80% of USVI land parcels, with the remaining parcels excluded due to a documented sewer network connection or lack of adequate soil data. Low failure rates (< 5% failure during period of analysis) were identified for less than 1% of the non-sewered land area. Figure 1-10, Figure 1-11, and Figure 1-12 illustrate failure rates across each island. Conventional OSDS failure statistics were summarized by 14-Digit Hydrologic Unit Code (HUC) and zoning type in order to assist USVI agencies with prioritization of alternative sewage management methods (Table 1-5 and Table 1-6, respectively). Estimates of the number of households using the sanitary sewage network and conventional OSDS for sewage disposal were also generated for each HUC using data from the 2000 U.S. Census (Table 1-5). Hydrologic units estimated to have the largest number of households using conventional OSDS for sewage disposal include NE St. Thomas (HUC 21020001010020), SE St. Thomas (HUC 21020001010030), and SW St. Croix (HUC 21020002020040). Conventional OSDS failure rate over the majority of the land area within these and all other hydrologic units was moderate (5-35% failure during period of analysis) to high (>35% failure during period of analysis). Among zoning types, high failure rates were found for 79-100% of the area within each zoning category.

OSDS failure analysis supports conclusions drawn from suitability analysis results. Each method indicates that conventional OSDS are inappropriate for use over much of the USVI land area due to the high likelihood for insufficiently treated wastewater to enter surface waters. Assumptions made during OSDS failure and suitability analysis should be noted when interpreting results. Suitability and failure rate totals represent values which are based on average soil, topographic, and hydrologic conditions of each land parcel. Any variability in these factors within individual parcels is not captured, and actual suitability/failure rates of conventional OSDS can differ from those reported if micro-site conditions within land parcels favor proper wastewater treatment and drainage. Despite this analytical limitation, it can be reasonably assumed that implementation of alternative wastewater disposal methods in non-sewered USVI land parcels should be a part of any pollution management strategy for reducing pathogen contamination.

**Table 1-5 Household sewage disposal method and conventional OSDS failure statistics for each 14-Digit Hydrologic Unit Code (HUC).[1]**

| HUC | Household Sewage Disposal[2] | | Conventional OSDS Failure Rate | | |
|---|---|---|---|---|---|
| | Sewer | Conventional OSDS | Low (<5%) | Moderate (5-35%) | High (>35%) |
| Northwest St. Croix (21020002010010) | 3,794 | 1,852 | 2% | 14% | 84% |
| Northcentral St. Croix (21020002010020) | 296 | 962 | <0.5% | 11% | 89% |
| Northeast St. Croix (21020002010030) | 680 | 1,204 | <0.5% | 22% | 78% |
| Southeast St. Croix (21020002020010) | 837 | 1,156 | <0.5% | 9% | 91% |
| Southparts St. Croix (21020002020020) | 2,852 | 2,249 | 1% | 8% | 91% |
| Airport St. Croix (21020002020030) | 888 | 6,93 | <0.5% | 10% | 89% |
| Southwest St. Croix (21020002020040) | 2,356 | 2,993 | <0.5% | 8% | 91% |
| North St. John (21020001020010) | 30 | 112 | <0.5% | 7% | 93% |
| Southeast St. John (21020001020020) | 39 | 453 | <0.5% | 25% | 75% |
| Southwest St. John (21020001020030) | 279 | 1,202 | 1% | 33% | 67% |
| Northwest St. Thomas (21020001010010) | 8,538 | 2,374 | 1% | 37% | 62% |
| Northeast St. Thomas (21020001010020) | 3,624 | 2,990 | 0% | <0.5% | 100% |
| Southeast St. Thomas (21020001010030) | 1,215 | 2,817 | <0.5% | 19% | 81% |
| Southwest St. Thomas (21020001010040) | 408 | 2021 | 3% | 3% | 95% |

[1] Failure rates for each HUC expressed as percentage of non-sewered land area in each failure rate range.
[2] Household sewage disposal statistics from 2000 U.S. Census.

**Table 1-6 Conventional OSDS failure statistics for each zoning type.[1]**

| Zoning Type | Failure Rate | | |
|---|---|---|---|
| | Low (<5%) | Medium (5-35%) | High (>35%) |
| Agriculture | 0% | 13% | 87% |
| Business/Commercial | 8% | 13% | 79% |
| Industry | 0% | <0.5% | 100% |
| Residential – Low Density | <0.5% | 19% | 80% |
| Residential – Med./High Density | <0.5% | 9% | 90% |
| Public | <0.5% | 12% | 88% |
| All | 1% | 16% | 83% |

[1] Failure rates for each zoning type expressed as percentage of non-sewered land area in each failure rate range.

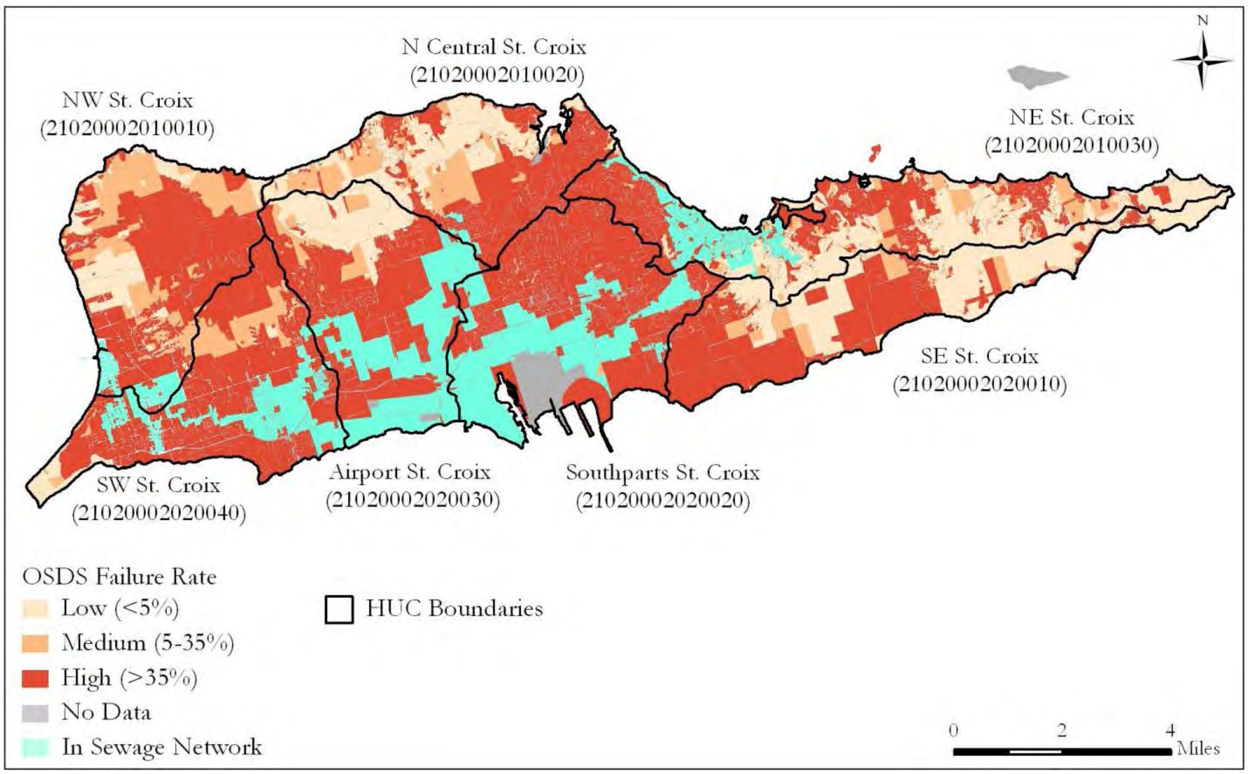



**Figure 1-10 Conventional OSDS failure rates for St. Croix.**

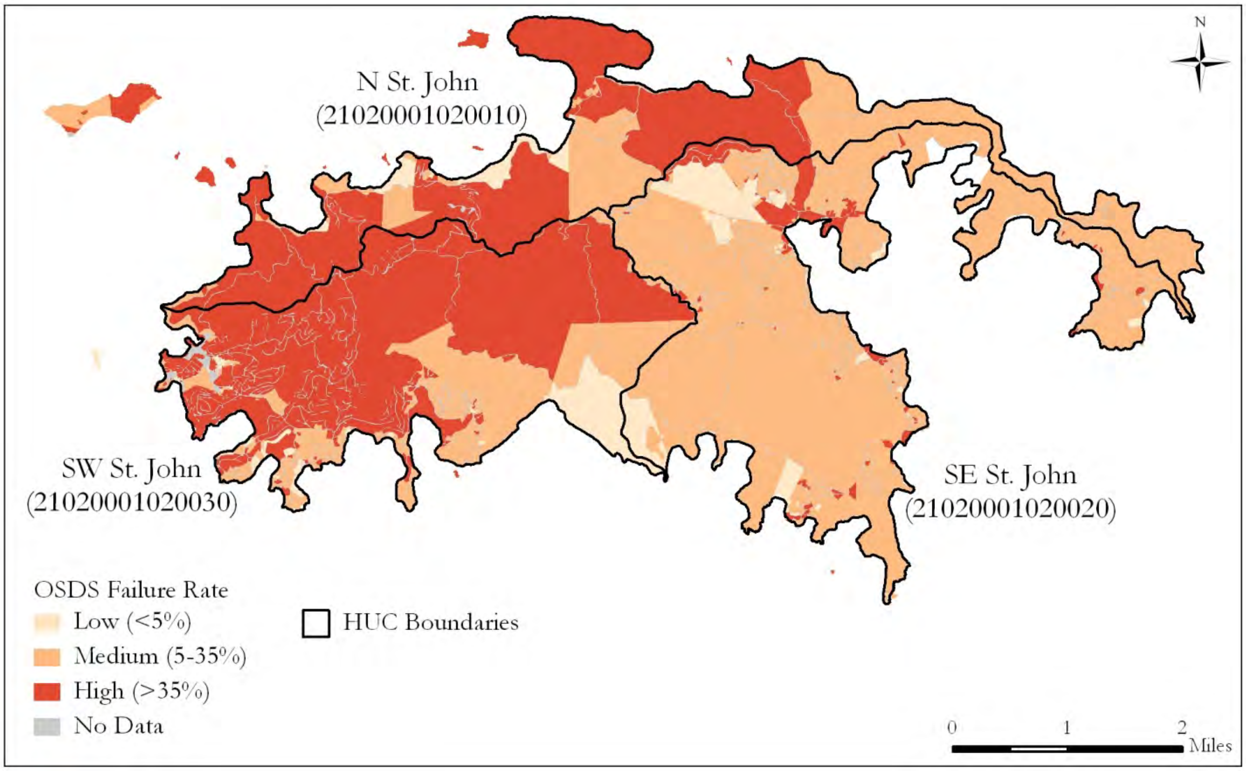



**Figure 1-11 Conventional OSDS failure rates for St. John.**

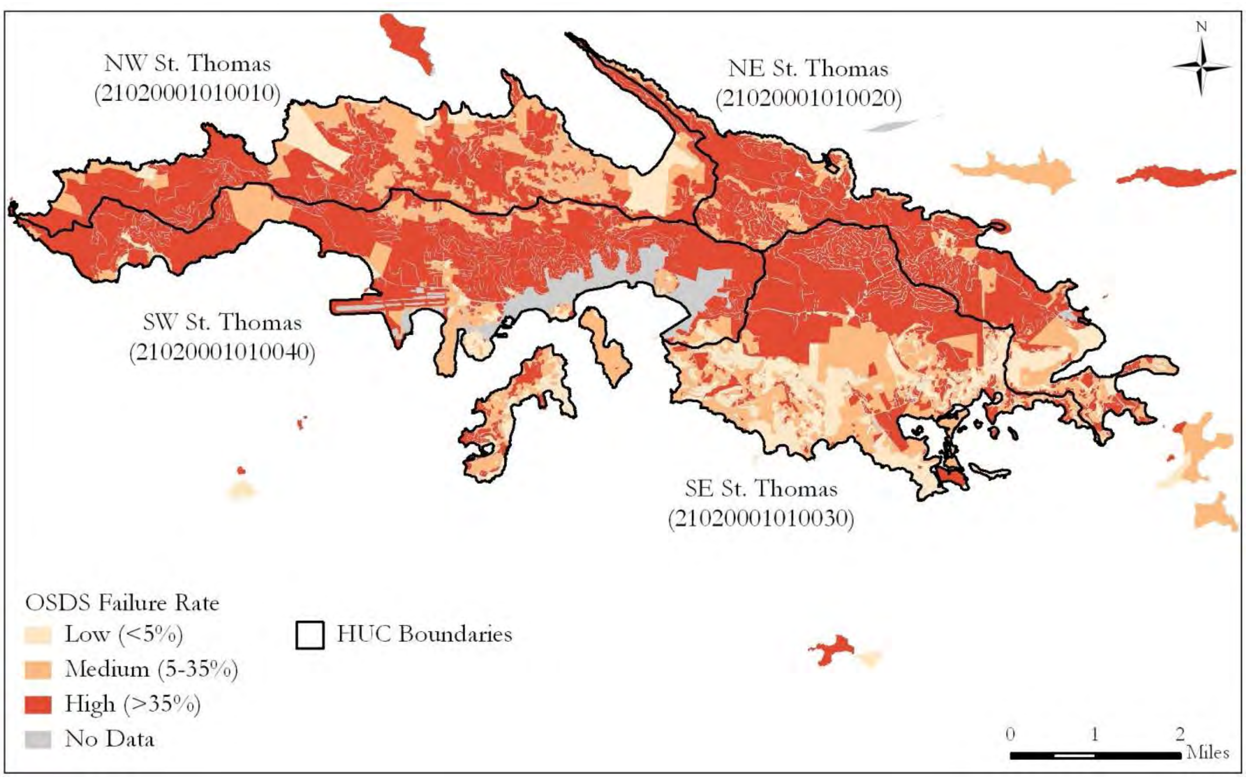



**Figure 1-12 Conventional OSDS failure rates for St. Thomas.**

## 1.6 Sanitary Sewage System Capacity Analysis

Proper disposal and treatment of wastewater from residences and businesses on USVI land parcels unsuitable for both conventional and alternative OSDS can be attained through connection to the WMA sanitary sewage system. Eight wastewater treatment facilities are actively in use on the USVI (one on St. Croix, two on St. John, five on St. Thomas). These facilities receive an estimated 5.75 million gallons of wastewater per day and serve approximately 70,000 residents (60% of the USVI population) (U.S. Environmental Protection Agency, 2008). Table 1-7 summarizes estimates of current wastewater volume collected, population served, and facility design capacity for each island, as reported by the U.S. Environmental Protection Agency (2008). In addition to facility design capacity, estimates of facility capacity required to service all USVI households were derived (Table 1-7). These estimates were developed from 2008 Clean Watersheds Needs Survey (CWNS) (U.S. Environmental Protection Agency, 2008) and 2000 U.S. Census data using information on the number of sewered and non-sewered households and wastewater generation on each island.

**Table 1-7 Wastewater treatment facility use and capacity.**

| Island/Facility Name | Population Served[1] | Present Collected (MGD)[1,2] | Present Capacity (MGD)[1] | Required Capacity (MGD)[3] |
|---|---|---|---|---|
| *St. Croix* (Anguilla Treatment Facility) | *34,951* | *2.11* | *5.75* | *4.27* |
| *St. John* | *255* | *0.03* | *0.03* | *0.19* |
| Cruz Bay Treatment Facility | 205 | 0.02 | 0.02 | |
| George Simmonds Treatment Facility | 50 | 0.01 | 0.01 | |
| *St. Thomas* | *34,269* | *3.61* | *5.07* | *6.31* |
| Mangrove Lagoon Treatment Facility | 13,363 | 0.93 | 1.1 | |
| Vessup Bay Treatment Facility | 1,100 | 0.06 | 0.3 | |
| Bassview Estates Treatment Facility | 150 | 0.01 | 0.04 | |
| Bordeaux Treatment Facility | 125 | 0.01 | 0.13 | |
| Airport Treatment Facility | 19,531 | 2.6 | 3.5 | |

[1] From 2008 Clean Watersheds Needs Survey (U.S. Environmental Protection Agency, 2008).
[2] MGD = Millions of Gallons per Day.
[3] Facility capacity required to service all island households reported in the 2000 U.S. Census.

CWNS estimates show that wastewater treatment facilities on St. Croix and St. Thomas have reserve capacity to provide wastewater treatment to additional users. CWNS data indicate that St. John facilities are currently running at capacity, however, recent upgrades to the Cruz Bay treatment facility have expanded its capacity, though updated facility data were not available for this report. On the island of St. Croix, facility design capacity exceeds that needed to provide sewer service to all island households, while additional facilities or facility upgrades are needed to service all island households on St. Thomas.

Lacking complete as-built information on the gravity sewer collection system, the capacity of the current sewage system network to collect and deliver additional wastewater to treatment facilities was determined from estimates of sewage network pump station capacity. Pump station capacity estimates were based on pump station force main design specifications (piping materials and diameters) for each pump station (Virgin Islands Waste Management Authority, 2007) and industry recommended minimum and maximum force main velocities (3.0 feet/second and 8.0 feet/second, respectively) (New England

Interstate Water Pollution Control Commission, 1998). Pump station force main design specifications were made available for the island of St. Croix only. Table 1-8 summarizes three estimates of pump station capacity, each based on separate reported values of industry practice recommended sewer force main velocity. Capacity estimates for the three major pump stations on St. Croix (LBJ, Figtree, and Lagoon) are near or above the design capacity of the St. Croix wastewater treatment facility, and the estimated facility capacity required for service to all St. Croix households (see Table 1-7). Both the wastewater treatment facility and sewage network infrastructure of St. Croix are estimated to have sufficient capacity to support additional connections up to the total number of St. Croix households. It should be noted, however, that information related to connections between each pump station and areas served, and between pump stations and the wastewater treatment plant, were not available for St. Croix or any other island. A thorough analysis of individual pump stations, their service areas, and the wastewater collection system piping network is needed for proper sewer service expansion planning.

**Table 1-8 Facility design capacity of St. Croix pump stations.**

| Pump Station | Maximum Capacity[1] (MGD) | Average Capacity[2] (MGD) | Minimum Capacity[3] (MGD) |
|---|---|---|---|
| Pearl B Larsen | 0.5 | 0.4 | 0.2 |
| Port Terminal | 0.5 | 0.4 | 0.2 |
| Old Barracks Yard | 0.5 | 0.4 | 0.2 |
| LBJ | 17.8 | 12.3 | 6.7 |
| Humbug I | 0.5 | 0.4 | 0.2 |
| Humbug II | 0.5 | 0.4 | 0.2 |
| Figtree | 17.8 | 12.3 | 6.7 |
| Ricardo Richards | 0.5 | 0.4 | 0.2 |
| Barren Spot | 1.2 | 0.8 | 0.4 |
| Mon Bijou | 0.5 | 0.4 | 0.2 |
| William Delight | 1.2 | 0.8 | 0.4 |
| Campo Rico | 1.2 | 0.8 | 0.4 |
| Lagoon Street | 12.4 | 8.5 | 4.6 |
| Concordia | 0.5 | 0.4 | 0.2 |
| Bay Road | 0.5 | 0.4 | 0.2 |

[1] At sewer force main velocity = 8 feet per second.
[2] At sewer force main velocity = 5.5 feet per second.
[3] At sewer force main velocity = 3 feet per second.

## 1.7 Recommendations for Wastewater Management Planning

Based on results of the OSDS suitability, OSDS failure probability, and sanitary sewage system capacity analyses, the following recommendations were developed to help USVI planning and management agencies more effectively and efficiently manage wastewater so that pathogen contamination of USVI waters can be minimized:

1) **Existing conventional OSDS located in unsuitable areas should be replaced with alternative OSDS technologies or connected to the sanitary sewage system.**

Soil conditions over much of the USVI are conducive to failure of conventional OSDS. Replacement with alternative OSDS and/or sewer service expansion in these areas can mitigate wastewater pollution. Since sewage system expansion costs limit the number of new connections, several criteria must be considered to provide sewer service to the largest number of residents with the greatest need. These criteria include: current and projected population density, alternative OSDS suitability, local sewage network and treatment facility capacity, and proximity to current sewage network.

Figure 1-13 presents a flow chart for use in evaluating the necessary course of action for any non-sewered land parcel. Potential outcomes include installation/maintenance of a conventional or alternative OSDS (depending on suitability) or placement on a priority, intermediate, or long-term sewage system expansion plan. Land parcels given priority for sewage system expansion are those with the lowest expansion cost and highest population density. These include residential land parcels on the islands of St. Croix and St. Thomas (which are estimated to have sewage network and treatment facility capacity) that are in close proximity to the current sewage network. Intermediate expansion is proposed to include land parcels requiring large investments in sewage network infrastructure or treatment facility capacity, such as those on the island of St. John. Long-term expansion is limited to land parcels which do not currently support large populations.

In order to efficiently manage sewage system expansion, suitability of alternative OSDS methods should be assessed prior to assigning intermediate or long-term sewage network expansion status, and alternative OSDS should be implemented whenever possible. The constructed wetland OSDS is appropriate for a variety of site conditions that otherwise prevent OSDS use. Though other options may be available for a particular site, establishment of the constructed wetland OSDS as the preferred alternative method of the USVI OSDS program may help to streamline the replacement of conventional OSDS in unsuitable areas. In addition, consolidation of wastewater from individual households into neighborhood-scale wastewater treatment facilities/OSDS units in low density residential areas may help to increase OSDS program efficiency and reduce wastewater treatment costs. Such a program could involve planning and participation by local residents, and efforts to include interested stakeholders should be undertaken.

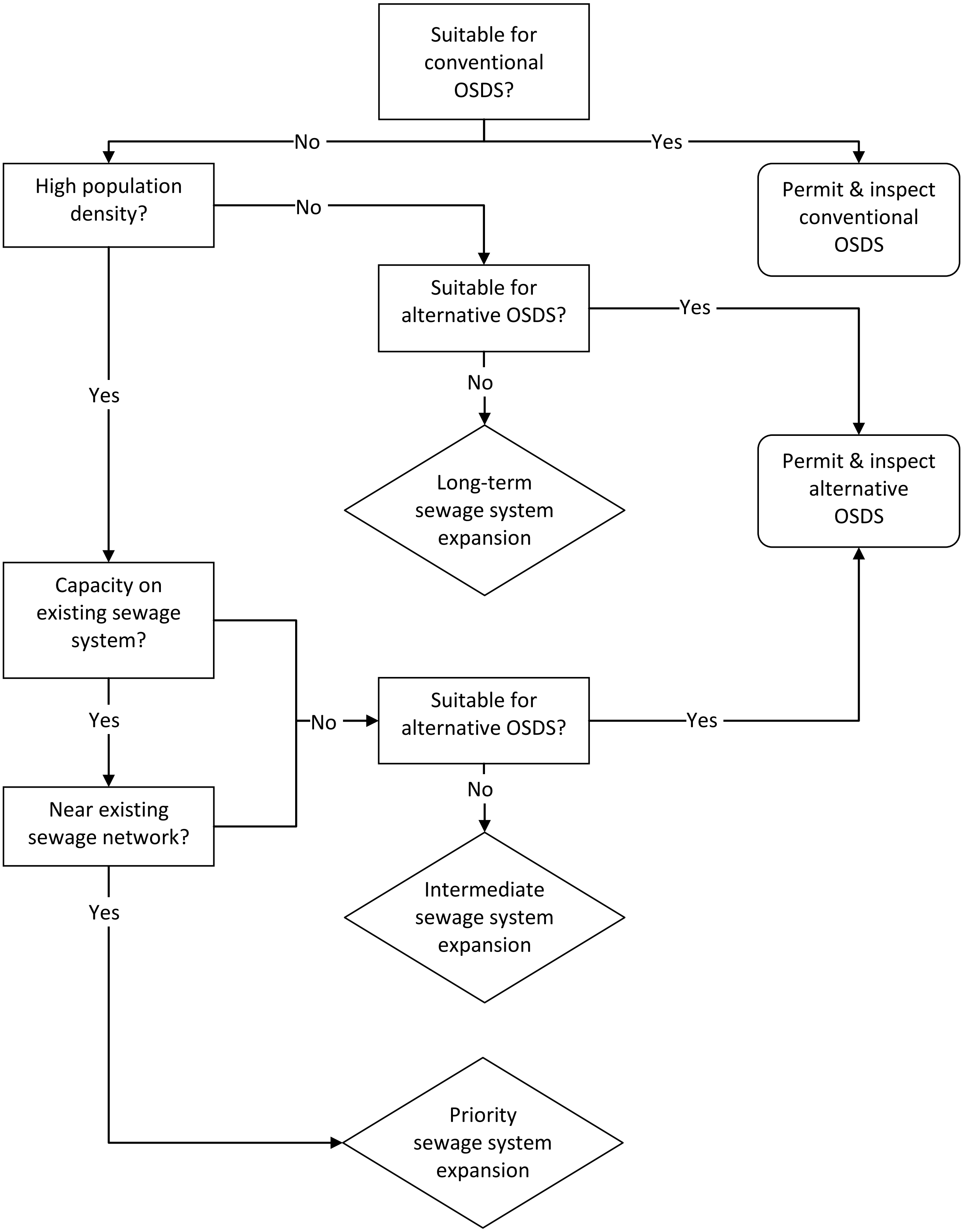



**Figure 1-13 Conventional OSDS replacement flow chart for USVI land parcels.**

2) **Conventional and alternative OSDS should continue to be managed through the DPNR permitting system to document, review, and approve system and site properties.**

The USVI OSDS program currently regulates the design, construction, and operation of OSDS through a permitting system. It is recommended that the OSDS permitting system be maintained and frequently updated to provide current information for all OSDS presently in use. This information should include a detailed review of site properties and OSDS design to determine site suitability for proper OSDS function. Evaluation of site properties should, at a minimum, consist of measurements of soil drainage characteristics and should follow guidelines summarized in the USVI Handbook on Onsite Sewage Treatment Systems (Virgin Islands Department of Planning and Natural Resources, 2006). Installation of any new OSDS should be preceded by a thorough site evaluation. Should evaluation of soil properties suggest a high probability for conventional OSDS failure, alternative OSDS may be installed where appropriate. It is recommended that inspection of all new and existing OSDS be conducted regularly to confirm proper function and maintenance.

## 1.8 Conclusions

Implementation of the recommendations presented in this report would require a significant investment of time and resources by the government of the USVI. The issue of OSDS failure and pathogen pollution necessitates coordination and cooperation among the USVI Department of Planning and Natural Resources, Waste Management Authority, and island residents. The recommendations provided herein are derived from analysis that has strongly supported the contention that OSDS failure is widespread and is a major contributor to pathogen pollution of coastal waters and groundwater. These recommendations are meant to serve as a framework for improved wastewater management. Detailed wastewater management planning for individual islands and watersheds are highly dependent on available funding and require an in-depth analysis of the current USVI sanitary sewage system. However, development and implementation of such plans will help to secure clean water for island residents, visitors, and the ecosystems on which they depend.

# 2 Watershed Planning

## 2.1 Precipitation Frequency Estimates

Nonpoint sources of pollution, including OSDS, impact water quality primarily through transport mechanisms mediated by storm events. Stormwater impacts on water quality are especially relevant in urban and developed areas and can be mitigated through implementation of stormwater best management practices (BMPs). For an individual storm event, BMP effectiveness is largely a function of storm magnitude and system design. Therefore, estimates of precipitation frequency are required for informed stormwater management planning and design.

Precipitation frequency estimates were developed for watersheds of the USVI from the National Oceanic and Atmospheric Administration's (NOAA) Precipitation Frequency Atlas of the United States (Bonnin, 2006). Precipitation frequency data in 90-meter resolution ASCII grid format were obtained from the NOAA Precipitation Data Frequency Server and processed using ArcGIS to derive watershed scale precipitation frequency estimates. Magnitudes for storms of 24-hour duration and return intervals of 1 year, 2 years, 5 years, 10 years, 25 years, 50 years, and 100 years were estimated for each 14-digit HUC (Table 2-1). For any given return interval, watersheds on the island of St. Croix generally receive the largest amount of rainfall, while St. Thomas watersheds receive the smallest. Inter-watershed variability (rainfall differences between watersheds within a particular return interval) and intra-watershed variability (rainfall differences between return intervals within a particular watershed) are highest for St. Croix watersheds. Estimated 100-year storm magnitudes are illustrated for watersheds on each island in Figure 2-1 (St. Croix), Figure 2-2 (St. John), and Figure 2-3 (St. Thomas).

**Table 2-1 Precipitation frequency estimates for each 14-digit Hydrologic Unit Code (HUC).**

| HUC | Magnitudes (inches) of 24-hour Duration Storms for Different Return Intervals | | | | | | |
|---|---|---|---|---|---|---|---|
| | ***1 Year*** | ***2 Years*** | ***5 Years*** | ***10 Years*** | ***25 Years*** | ***50 Years*** | ***100 Years*** |
| Northeast St. Croix (21020002010030) | 3.5 | 4.8 | 7.3 | 9.3 | 12.4 | 15.0 | 17.8 |
| Southeast St. Croix (21020002020010) | 3.6 | 4.9 | 7.3 | 9.4 | 12.6 | 15.2 | 18.1 |
| Northcentral St. Croix (21020002010020) | 3.7 | 5.0 | 7.5 | 9.7 | 12.9 | 15.6 | 18.6 |
| Airport St. Croix (21020002020030) | 3.8 | 5.2 | 7.9 | 10.2 | 13.5 | 16.4 | 19.6 |
| Southwest St. Croix (21020002020040) | 3.7 | 5.0 | 7.6 | 9.7 | 12.9 | 15.7 | 18.6 |
| Northwest St. Croix (21020002010010) | 3.9 | 5.3 | 8.0 | 10.3 | 13.7 | 16.6 | 19.8 |
| Southparts St. Croix (21020002020020) | 3.6 | 4.9 | 7.4 | 9.5 | 12.6 | 15.2 | 18.1 |
| North St. John (21020001020010) | 3.1 | 4.3 | 6.4 | 8.2 | 10.9 | 13.3 | 15.8 |
| Southeast St. John (21020001020020) | 3.1 | 4.2 | 6.4 | 8.2 | 10.9 | 13.2 | 15.7 |
| Southwest St. John (21020001020030) | 3.2 | 4.3 | 6.5 | 8.4 | 11.2 | 13.6 | 16.1 |
| Southwest St. Thomas (21020001010040) | 2.9 | 3.9 | 5.8 | 7.5 | 9.9 | 12.0 | 14.2 |
| Southeast St. Thomas (21020001010030) | 3.0 | 4.0 | 6.1 | 7.8 | 10.3 | 12.5 | 14.8 |
| Northeast St. Thomas (21020001010020) | 2.9 | 3.9 | 5.8 | 7.5 | 9.8 | 11.8 | 13.9 |
| Northwest St. Thomas (21020001010010) | 2.9 | 4.0 | 6.0 | 7.7 | 10.2 | 12.4 | 14.7 |

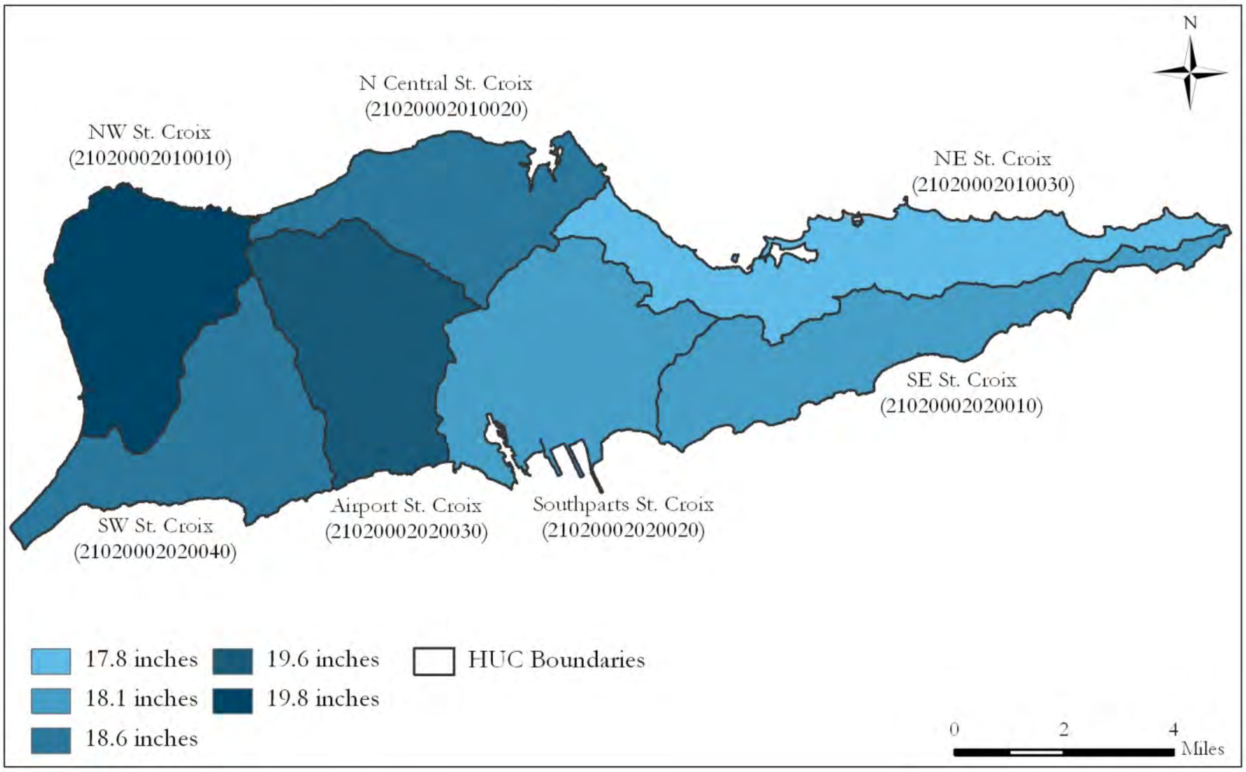



**Figure 2-1 100-year storm magnitude for St. Croix watersheds.**

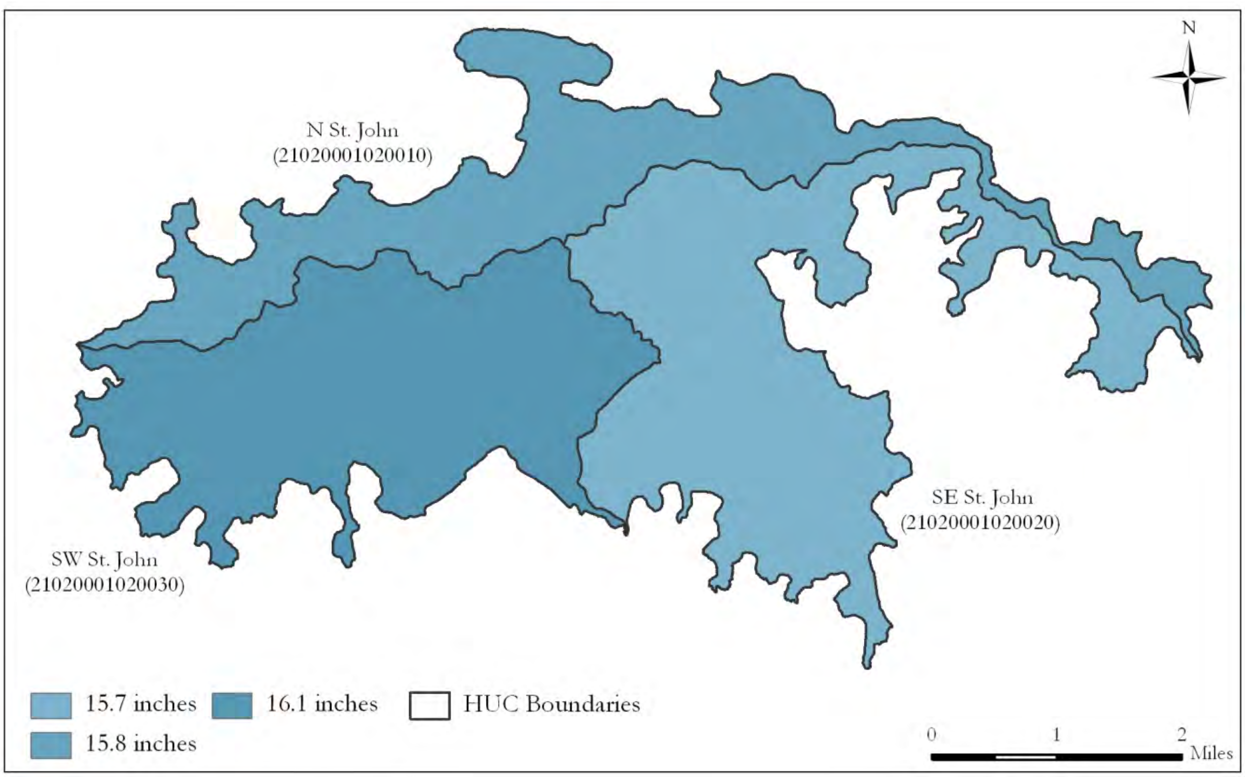



**Figure 2-2 100-year storm magnitude for St. John watersheds.**

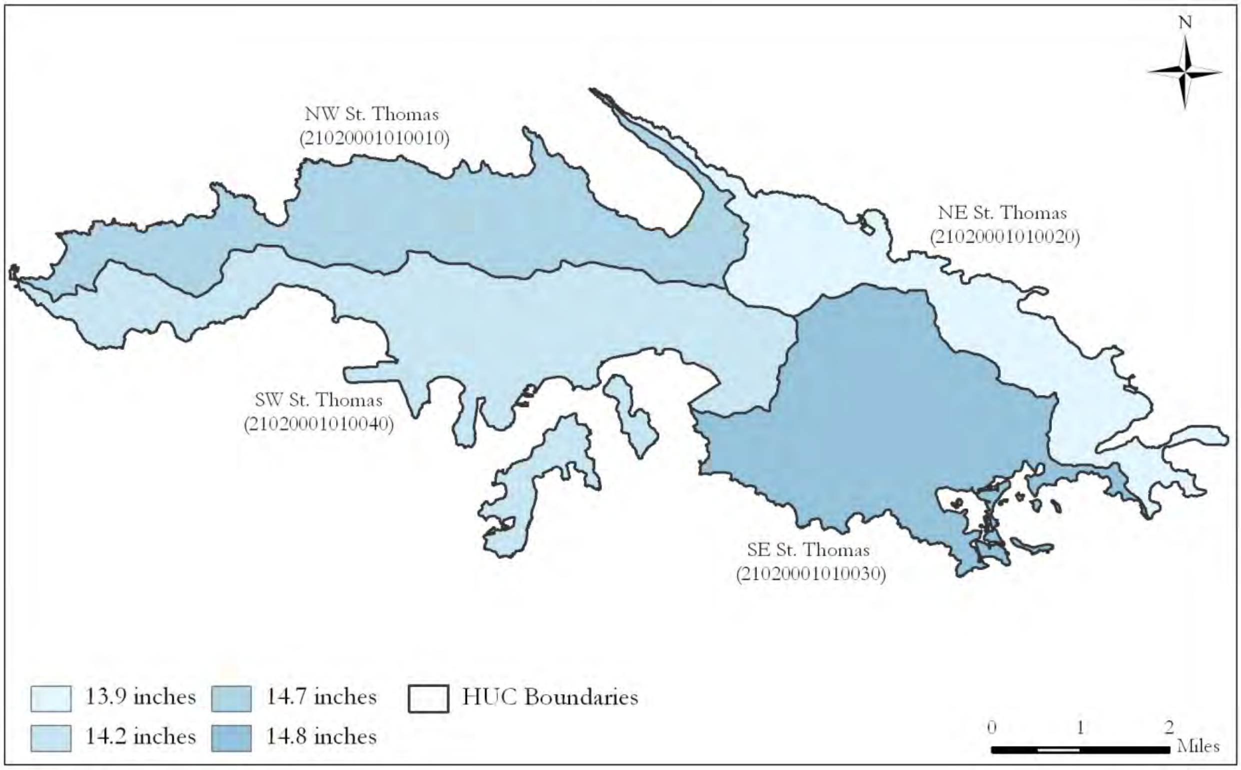



**Figure 2-3 100-year storm magnitude for St. Thomas watersheds.**

USVI precipitation characteristics were further assessed through analysis of long-term daily rainfall records. Daily rainfall measurements taken at 10 rain gage stations throughout the USVI were provided by the U.S. EPA from the NOAA National Climatic Data Center archive. Rain gage stations are generally located at relatively low elevations (≤ 200 feet above sea level). Data from each station were used to calculate the following descriptive statistics of rainfall frequency and seasonality:

- 95$^{th}$ percentile storm depth
- 90$^{th}$ percentile storm depth
- Mean storm depth
- Number of days per year with storm depth greater than 0.5 inches in a 24-hour period
- Number of days per month with storm depth greater than 0.5 inches in a 24-hour period

Spatial and temporal characteristics of rain gage stations used for precipitation frequency/seasonality calculations are provided in Table 2-2. Daily rainfall records covered a period of 28-39 years and include data through 2008. The number of missing data records was as low as 4-5% of all records for 2 stations on St. Croix (Christiansted Airport and East Hill) and as high as 37% of all records for the Redhook Bay station on St. Thomas.

Estimated values of 90$^{th}$ percentile, 95$^{th}$ percentile, and mean storm depth for each rain gage station are summarized in Table 2-3. A low degree of variability was evident between stations for each statistic. Values of 90$^{th}$ percentile storm depth ranged from 0.9 inches to 1.3 inches, and estimated 95$^{th}$

percentile storm depth ranged from 1.4 to 2.0 inches. Estimated mean storm depth for all stations was approximately 0.5 inches. The average number of days per year with large storm events (storm depth greater than 0.5 inches) also showed minor variability between stations (14-21 days, Table 2-4). These days were generally evenly distributed throughout the year (Table 2-4), though a low degree of seasonality was evident in select stations (highest counts in the months of September-November).

**Table 2-2 Location and data record characteristics for USVI rain gage stations used for calculation of 90th percentile, 95th percentile, and mean storm depth, and large storm frequency/seasonality.**

| Station Name & ID | Island | Elevation (ft) | Record Start Date | Record End Date | Record Length (years) | % Missing Records |
|---|---|---|---|---|---|---|
| Christiansted Airport (670198) | St. Croix | 44 | 1981 | 2008 | 28 | 4 |
| Christiansted Fort (671740) | St. Croix | 30 | 1972 | 2008 | 37 | 32 |
| East Hill (672560) | St. Croix | 120 | 1972 | 2008 | 37 | 5 |
| Montpellier (674900) | St. Croix | 200 | 1979 | 2008 | 30 | 10 |
| Coral Bay (671790) | St. John | 30 | 1972 | 2008 | 37 | 20 |
| Cruz Bay (671980) | St. John | 8 | 1972 | 2008 | 37 | 14 |
| East End (672551) | St. John | 150 | 1972 | 2008 | 37 | 17 |
| Redhook Bay (677600) | St. Thomas | 2 | 1980 | 2008 | 29 | 37 |
| Charlotte Amalie Airport (678905) | St. Thomas | 20 | 1972 | 2010 | 39 | 14 |
| Wintberg (679450) | St. Thomas | 645 | 1972 | 2008 | 37 | 8 |

**Table 2-3 Estimated storm depth statistics for each rain gage station.**

| Station Name & ID | 90th Percentile Storm Depth (inches) | 95th Percentile Storm Depth (inches) | Mean Storm Depth (inches) |
|---|---|---|---|
| Christiansted Airport (670198) | 0.9 | 1.4 | 0.5 |
| Christiansted Fort (671740) | 1.0 | 1.5 | 0.5 |
| East Hill (672560) | 1.0 | 1.6 | 0.5 |
| Montpellier (674900) | 1.1 | 1.6 | 0.5 |
| Coral Bay (671790) | 0.9 | 1.4 | 0.5 |
| Cruz Bay (671980) | 1.1 | 1.7 | 0.5 |
| East End (672551) | 1.2 | 1.9 | 0.5 |
| Redhook Bay (677600) | 1.3 | 2.0 | 0.6 |
| Charlotte Amalie Airport (678905) | 1.0 | 1.5 | 0.5 |
| Wintberg (679450) | 1.1 | 1.6 | 0.5 |

**Table 2-4 Estimated large storm (> 0.5 inches) frequency and seasonality for each rain gage station.**

| Station Name & ID | Number of Days per Year/Month with Storm Depth > 0.5 inches | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Annual | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
| Christiansted Airport (670198) | 17 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 1 |
| Christiansted Fort (671740) | 14 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 1 | 2 | 2 | 2 | 1 |
| East Hill (672560) | 16 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 3 | 2 |
| Montpellier (674900) | 21 | 1 | 0 | 1 | 2 | 2 | 1 | 2 | 2 | 3 | 3 | 3 | 2 |
| Coral Bay (671790) | 16 | 1 | 1 | 0 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 |
| Cruz Bay (671980) | 16 | 0 | 0 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 3 | 2 | 1 |
| East End (672551) | 19 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 3 | 2 | 2 |
| Redhook Bay (677600) | 16 | 1 | 0 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 |
| Charlotte Amalie Airport (678905) | 16 | 1 | 0 | 0 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 |
| Wintberg (679450) | 20 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 3 | 3 | 3 | 2 |

## 2.2 Land Use Change Analysis

Urban and agricultural land uses have the potential to serve as nonpoint sources of pollution. Changes in land use patterns are primarily a function of local population changes and economic drivers. Population growth in the USVI proceeded at a rate of 0.7% per year from 1990 to 2000, yet slowed to an estimated rate of only 0.1% from 2000 to 2010 (Table 2-5).

**Table 2-5 USVI Population (U.S. Census Bureau, 2010).**

| Island | 1990 | 2000 | 2010 |
|---|---|---|---|
| St. Thomas | 48,166 | 51,181 | NA |
| St. Croix | 50,139 | 53,234 | NA |
| St. John | 3,504 | 4,197 | NA |
| Total | 101,809 | 108,612 | 109,792[1] |

[1] Population estimates from the 2010 Census are not yet available for the USVI. This number represents the Census Bureau's projected population for 2010.

As indicated by the 2007 U.S. Census of Agriculture, livestock inventory on the USVI decreased substantially between 1997 and 2007 (Table 2-6) (U.S. Department of Agriculture, 2009). This decrease primarily occurred on St. Croix, with livestock populations on St. John and St. Thomas remaining relatively stable. Although these data are only reported at the island level, data from the Virgin Islands Department of Agriculture (2010) indicate the locations of individual animals, allowing for an understanding of the relative density of livestock by HUC (Table 2-6). Livestock populations from both datasets were converted to Animal Equivalent Units (AEUs) based on conversion factors used by the U.S. Natural Resources Conservation Service (NRCS) (U.S. Department of Agriculture, 2010). This facilitates comparison of the two datasets. However, differences in the types of animals included within each data set and differences in data collection methodology limit the ability to make direct comparisons between the two sources. In addition, the Virgin Islands Department of Agriculture data were only provided for a single time period, which prevents a trend analysis at the HUC scale.

**Table 2-6 Livestock counts by 14-digit Hydrologic Unit Code (HUC), in Animal Equivalent Units (AEUs).**

| Island / HUC | Livestock in the USVI | |
|---|---|---|
| | Virgin Islands Department of Agriculture (2004, total AEUs) | U.S. Census of Agriculture (% change in AEUs, 1997-2007) |
| ***U.S. Virgin Islands*** | ***6,472*** | ***-54%*** |
| ***St. Croix*** | ***4,698*** | -58% |
| Northwest St. Croix (21020002010010) | 502 | |
| Northcentral St. Croix (21020002010020) | 676 | |
| Northeast St. Croix (21020002010030) | 333 | |
| Southeast St. Croix (21020002020010) | 443 | |
| Southparts St. Croix (21020002020020) | 417 | |
| Airport St. Croix (21020002020030) | 1,999 | |
| Southwest St. Croix (21020002020040) | 328 | |
| ***St. John*** | ***359*** | -0.4% |
| North St. John (21020001020010) | N/A | |
| Southeast St. John (21020001020020) | 232 | |
| Southwest St. John (21020001020030) | 127 | |
| ***St. Thomas*** | ***1,415*** | |
| Northwest St. Thomas (21020001010010) | 850 | |
| Northeast St. Thomas (21020001010020) | 97 | |
| Southeast St. Thomas (21020001010030) | 227 | |
| Southwest St. Thomas (21020001010040) | 241 | |

Recent trends in human population and livestock inventory on the USVI are likely to result in changes to land use patterns and, consequently, potential nonpoint source pollution loading. This hypothesis was evaluated through a land use change analysis. Land use data for the USVI were acquired from two different sources. For 1992 and 2001, Landsat images were acquired from the USGS EarthExplorer data portal for Path 4, Rows 47 (St. Thomas and St. John) and 48 (St. Croix). The 1992 imagery was acquired on August 12, 1992 using the Landsat 4 Thematic Mapper sensor, and the 2001 imagery was acquired on January 25, 2001 using the Landsat 7 Enhanced Thematic Mapper + sensor (with scanline correction on). These images have native resolution of 30 meters and were chosen to minimize the impact of cloud cover on the analysis. A supervised land cover classification was performed using training sets for each land cover class distributed across all three islands (87 training sets in 1992, and 102 training sets in 2001). The classification was performed using the maximum likelihood classification algorithm on Landsat Bands 1-5 and 7 within ArcGIS version 10. Smoothing of the final classification, using a 5x5 majority filter, was performed on the final classification to reduce speckling. In areas where clouds obscured the ground view in either 1992 or 2001, the land cover class was assumed to have remained constant between the two time periods. Land cover data for 2007 was acquired from the NOAA Coastal Change Analysis Program. The NOAA classifications were produced through interpretation of imagery acquired by the Quickbird satellite (2.4 meter resolution).

The classification scheme was constant between the three images, except for the absences of a “low density urban” class in the 2007 dataset. The high resolution of the native 2007 imagery allowed for the direct classification of impervious and developed open space cover types, instead of classification as the more general “low density urban” class, which traditionally consists of a mix of impervious and other pervious cover types. To resolve this difference, a low density urban class was created for the 2007 dataset using a 12x12 (30m x 30m, or 144 pixels) neighborhood analysis. Neighborhoods where 30% of the analyzed pixels were “impervious” and 8% of the analyzed pixels were “open space developed” were classified as “low density residential.” Smoothing of this reclassification, using a 5x5 majority filter, was performed to reduce speckling. This reclassification method resulted in a suitable spatial match between the resulting low density urban area and known residential neighborhoods visible in the 1992 and 2001 datasets. Further, this reclassification method facilitated comparison of all data sets for the purpose of determining changes in land use.

Undeveloped areas (e.g., forests, shrublands, wetlands, barren areas, and open water) are widespread in the USVI (Table 2-7, Figure 2-4). In 2007, 75.8% of the USVI land area was undeveloped, while only 0.4% was in agricultural use, and 23.8% was classified as urban. Land use patterns on the USVI are not static, however, and changes between 1992 and 2007 (Table 2-8 and Figure 2-4) have generally followed the trends that might be expected in light of the human population and livestock inventory changes presented in Table 2-5 and Table 2-6. From 1992 to 2001, when human population was growing at a rate of 0.7% per year, high density urban land use expanded from 3.8% to 5.9%. High density urban land use continued to expand between 2001 and 2007, rising to 7.4% of total land area. This urbanization trend was accompanied by decreases in both undeveloped areas (82.6% in 1992, 75.8% in 2007) and, to a lesser extent, agricultural areas (0.6% in 1992, 0.4% in 2007). Changes in low density urban coverage were observed between 2001 and 2007, but this is most likely attributable to the conservative estimation of low density urban area using the reclassification method described above. Further, slight increases in water area and wetland coverage between 2001 and 2007 were observed, especially on St. John. This is most likely a function of higher than average precipitation in 2007, which resulted in high water in forested wetland areas. These forested wetlands were most commonly classified as ‘forest’ in previous years due to lower water and dense forest canopy.

Land use change has not been uniform across the islands either. Relative rates of urbanization on St. John far outpaced those on St. Croix or St. Thomas from 1992 to 2001. From 2001 to 2007, urbanization was more consistent across the islands. Conversion of forest/shrub cover to developed open space on St. Croix was significant from 2001-2007. This is likely attributable in part to development activity and in some part to classification differences between the two images. Agricultural land decreased most substantially on St. Croix from 1992 to 2001. Agricultural uses represent a negligible portion of overall land use on the other islands. Overall, urbanization on the USVI continues to increase, while natural land cover types decrease.

**Table 2-7 2007 land cover by 14-digit Hydrologic Unit Code (HUC).**

| Island/HUC | HD Urban | LD Urban | Dev. Open Space | Agriculture | Forest & Shrub | Wetland | Barren | Water |
|---|---|---|---|---|---|---|---|---|
| ***U.S. Virgin Islands*** | ***7.4%*** | ***10.1%*** | ***6.3%*** | ***0.4%*** | ***70.7%*** | ***1.8%*** | ***2.3%*** | ***1.0%*** |
| ***St. Croix*** | ***6.6%*** | ***10.9%*** | ***8.6%*** | ***0.6%*** | ***68.6%*** | ***1.3%*** | ***2.3%*** | ***1.0%*** |
| Northwest St. Croix (21020002010010) | 3.2% | 4.1% | 3.8% | 0.2% | 86.9% | 0.7% | 0.9% | 0.2% |
| Northcentral St. Croix (21020002010020) | 5.0% | 8.0% | 5.4% | 0.6% | 77.2% | 2.5% | 0.7% | 0.7% |
| Northeast St. Croix (21020002010030) | 6.3% | 15.0% | 9.4% | 0.0% | 65.9% | 1.3% | 1.6% | 0.5% |
| Southeast St. Croix (21020002020010) | 2.3% | 3.3% | 3.0% | 0.0% | 85.9% | 1.1% | 3.3% | 1.2% |
| Southparts St. Croix (21020002020020) | 18.0% | 17.9% | 11.5% | 0.0% | 43.3% | 1.6% | 6.5% | 1.2% |
| Airport St. Croix (21020002020030) | 4.9% | 10.3% | 12.0% | 3.0% | 66.5% | 1.7% | 1.1% | 0.7% |
| Southwest St. Croix (21020002020040) | 4.5% | 15.9% | 13.9% | 0.6% | 61.0% | 0.1% | 1.6% | 2.5% |
| ***St. John*** | ***5.0%*** | ***2.0%*** | ***0.7%*** | ***0.0%*** | ***84.4%*** | ***4.2%*** | ***1.9%*** | ***1.8%*** |
| North St. John (21020001020010) | 2.8% | 0.6% | 0.8% | 0.0% | 89.8% | 3.8% | 0.9% | 1.4% |
| Southeast St. John (21020001020020) | 4.8% | 1.6% | 0.6% | 0.0% | 83.1% | 4.7% | 2.5% | 2.7% |
| Southwest St. John (21020001020030) | 6.9% | 3.6% | 0.7% | 0.0% | 81.7% | 4.0% | 1.9% | 1.1% |
| ***St. Thomas*** | ***11.2%*** | ***13.1%*** | ***3.3%*** | ***0.0%*** | ***67.4%*** | ***1.8%*** | ***2.4%*** | ***0.8%*** |
| Northwest St. Thomas (21020001010010) | 7.9% | 2.9% | 1.4% | 0.0% | 83.7% | 2.0% | 1.9% | 0.2% |
| Northeast St. Thomas (21020001010020) | 12.0% | 14.4% | 4.8% | 0.0% | 63.9% | 0.9% | 3.1% | 0.9% |
| Southeast St. Thomas (21020001010030) | 10.2% | 18.8% | 3.1% | 0.0% | 61.1% | 3.3% | 2.6% | 0.9% |
| Southwest St. Thomas (21020001010040) | 14.2% | 15.5% | 4.1% | 0.0% | 62.1% | 0.9% | 2.2% | 1.0% |

Table 2-8 Change in land cover, 1992-2001.

| Island/HUC | HD Urban | LD Urban | Dev. Open Space | Agriculture | Forest & Shrub | Wetland | Barren | Water |
|---|---|---|---|---|---|---|---|---|
| ***U.S. Virgin Islands*** | ***2.0%*** | ***1.9%*** | ***1.3%*** | ***-0.4%*** | ***0.0%*** | ***0.0%*** | ***-4.8%*** | ***-0.1%*** |
| ***St. Croix*** | ***2.2%*** | ***1.6%*** | ***1.4%*** | ***-0.5%*** | ***0.8%*** | ***0.0%*** | ***-5.4%*** | ***-0.1%*** |
| Northwest St. Croix (21020002010010) | 0.8% | 2.1% | -0.7% | -0.6% | -0.5% | 0.0% | -1.0% | 0.0% |
| Northcentral St. Croix (21020002010020) | 1.5% | 0.5% | 0.1% | -0.5% | 0.6% | 0.0% | -2.2% | 0.0% |
| Northeast St. Croix (21020002010030) | 4.1% | -2.5% | 1.0% | -0.2% | 14.2% | 0.0% | -16.5% | -0.1% |
| Southeast St. Croix (21020002020010) | 2.6% | 3.6% | 0.0% | -1.4% | 3.0% | 0.1% | -8.0% | 0.1% |
| Southparts St. Croix (21020002020020) | 3.2% | 5.0% | 3.1% | -0.8% | -5.0% | 0.1% | -5.6% | -0.1% |
| Airport St. Croix (21020002020030) | 1.6% | 5.0% | 5.0% | 0.3% | -10.6% | 0.1% | -1.3% | 0.0% |
| Southwest St. Croix (21020002020040) | 1.4% | -3.4% | 0.6% | -0.6% | 3.9% | 0.0% | -1.8% | -0.2% |
| ***St. John*** | ***1.3%*** | ***2.0%*** | ***1.4%*** | ***0.0%*** | ***-0.8%*** | ***-0.1%*** | ***-3.8%*** | ***0.0%*** |
| North St. John (21020001020010) | 0.2% | 0.0% | 0.6% | 0.0% | 0.6% | -0.2% | -1.2% | 0.0% |
| Southeast St. John (21020001020020) | 2.2% | 3.5% | 2.3% | 0.0% | -1.5% | 0.0% | -6.4% | -0.2% |
| Southwest St. John (21020001020030) | 1.2% | 1.8% | 1.1% | 0.0% | -1.3% | -0.1% | -3.0% | 0.2% |
| ***St. Thomas*** | ***1.9%*** | ***2.9%*** | ***0.8%*** | ***-0.1%*** | ***-1.7%*** | ***0.0%*** | ***-3.7%*** | ***-0.1%*** |
| Northwest St. Thomas (21020001010010) | 0.9% | 0.3% | -0.1% | -0.1% | -0.2% | 0.0% | -0.6% | -0.2% |
| Northeast St. Thomas (21020001010020) | 1.5% | 3.3% | 2.4% | -0.1% | -5.0% | 0.0% | -2.1% | 0.0% |
| Southeast St. Thomas (21020001010030) | 3.1% | 4.9% | 0.4% | -0.1% | -2.2% | -0.2% | -5.9% | -0.1% |
| Southwest St. Thomas (21020001010040) | 2.0% | 3.0% | 0.8% | 0.0% | -0.5% | 0.1% | -5.2% | -0.2% |

**Table 2-9 Change in land cover, 2001-2007.**

| Island/HUC | HD Urban | LD Urban | Dev. Open Space | Agriculture | Forest & Shrub | Wetland | Barren | Water |
|---|---|---|---|---|---|---|---|---|
| ***U.S. Virgin Islands*** | ***1.5%*** | ***-3.9%*** | ***4.2%*** | ***0.1%*** | ***-5.5%*** | ***1.5%*** | ***1.5%*** | ***0.6%*** |
| ***St. Croix*** | ***0.2%*** | ***-5.1%*** | ***6.2%*** | ***0.2%*** | ***-4.3%*** | ***1.0%*** | ***1.5%*** | ***0.3%*** |
| Northwest St. Croix (21020002010010) | 2.2% | 0.2% | 3.1% | 0.1% | -7.3% | 0.7% | 0.8% | 0.2% |
| Northcentral St. Croix (21020002010020) | 3.2% | -0.3% | 3.4% | 0.2% | -10.1% | 2.4% | 0.6% | 0.7% |
| Northeast St. Croix (21020002010030) | -0.3% | -6.5% | 8.3% | 0.0% | -4.2% | 1.3% | 1.1% | 0.4% |
| Southeast St. Croix (21020002020010) | -1.1% | -6.5% | 2.5% | 0.0% | 5.1% | 0.5% | -1.1% | 0.6% |
| Southparts St. Croix (21020002020020) | -4.2% | -7.3% | 7.8% | -0.1% | -3.2% | 1.0% | 6.4% | -0.3% |
| Airport St. Croix (21020002020030) | 1.0% | -1.6% | 4.7% | 1.0% | -7.5% | 1.6% | 0.3% | 0.7% |
| Southwest St. Croix (21020002020040) | 2.0% | -12.8% | 12.9% | 0.5% | -4.1% | 0.0% | 1.1% | 0.3% |
| ***St. John*** | ***2.9%*** | ***-0.8%*** | ***-0.8%*** | ***0.0%*** | ***-8.0%*** | ***4.2%*** | ***1.3%*** | ***1.3%*** |
| North St. John (21020001020010) | 2.3% | 0.6% | 0.1% | 0.0% | -8.8% | 3.7% | 0.8% | 1.2% |
| Southeast St. John (21020001020020) | 1.3% | -2.4% | -1.8% | 0.0% | -5.6% | 4.6% | 1.6% | 2.1% |
| Southwest St. John (21020001020030) | 5.0% | -0.1% | -0.4% | 0.0% | -10.2% | 4.0% | 1.2% | 0.6% |
| ***St. Thomas*** | ***4.4%*** | ***-2.5%*** | ***1.7%*** | ***0.0%*** | ***-7.3%*** | ***1.1%*** | ***1.9%*** | ***0.7%*** |
| Northwest St. Thomas (21020001010010) | 6.3% | 2.5% | 1.2% | 0.0% | -14.0% | 1.9% | 1.9% | 0.1% |
| Northeast St. Thomas (21020001010020) | 8.0% | 0.7% | 1.2% | 0.0% | -13.6% | 0.7% | 2.3% | 0.7% |
| Southeast St. Thomas (21020001010030) | 4.8% | -9.9% | 1.0% | 0.0% | 0.9% | 1.0% | 1.4% | 0.8% |
| Southwest St. Thomas (21020001010040) | 0.6% | -2.3% | 2.8% | 0.0% | -4.6% | 0.6% | 2.0% | 0.9% |

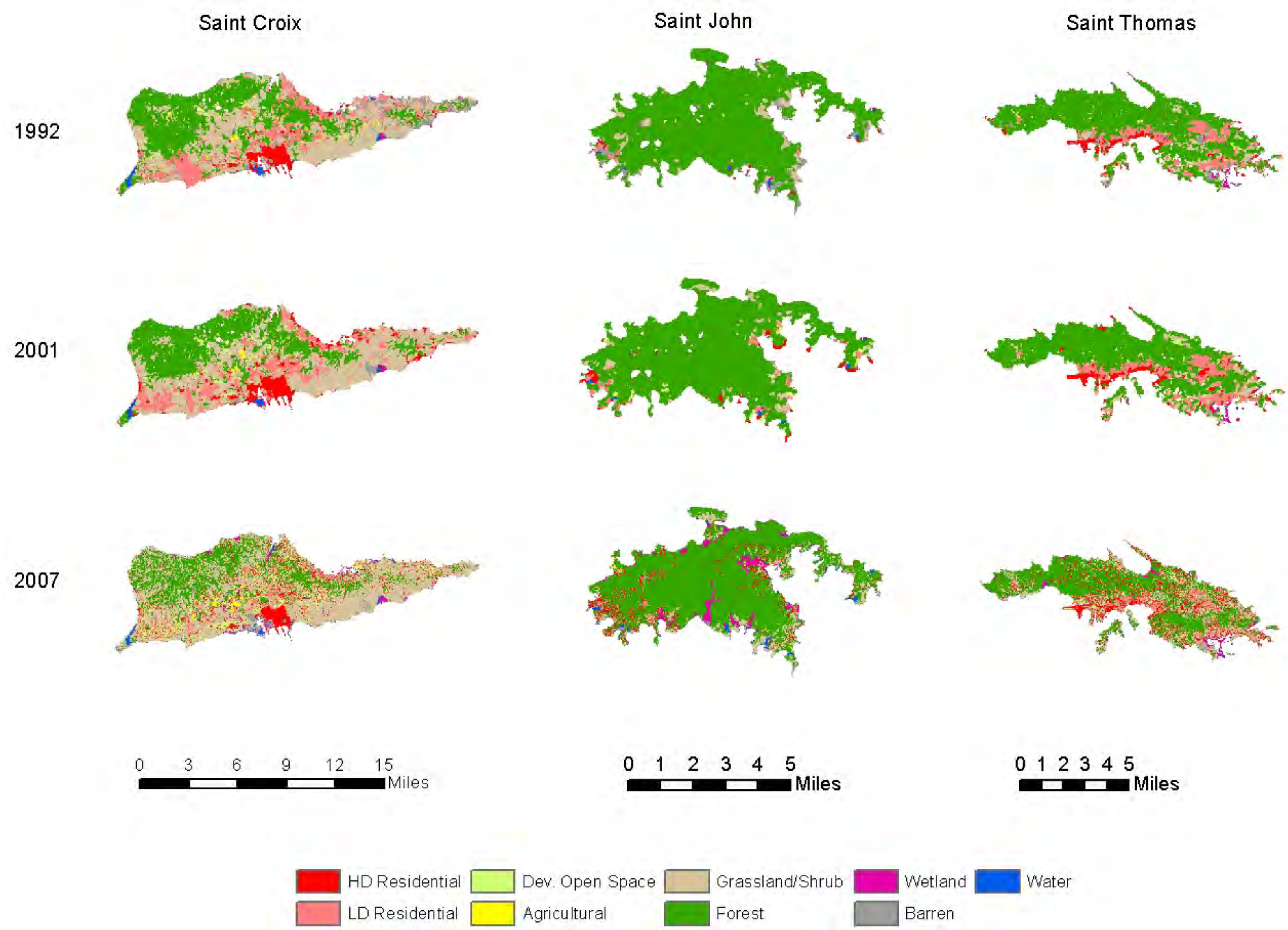



**Figure 2-4 Land use in the U.S. Virgin Islands, 1992-2007.**

## 2.3 Impacts of Land Use Change on Runoff

Changes in land use have the potential to result in significant changes in stormwater runoff and nonpoint source pollutant loading. The Long-Term Hydrologic Impact Assessment (L-THIA) tool was used to estimate the effects of land use changes in the USVI on runoff and fecal coliform loading. L-THIA is a tool that planners can use to assess the impacts of land use changes on runoff volume and nonpoint source pollutant loading. The tool is implemented as an online calculator and as an extension to the ESRI© ArcView 3.2 software package. For this analysis, the GIS version of the tool (Bhaduri, Harbor, Engel, & Grove, 2000) was used.

L-THIA determines runoff from precipitation, land use, and soils data using the Soil Conservation Service Curve Number (CN) approach (U.S. Department of Agriculture Natural Resource Conservation Service, 1986). The CN approach estimates the proportion of precipitation expected to runoff as stormwater based on storm intensity, land use, and the characteristics of the underlying soils. Curve numbers in the USVI range from 0 to 95, with higher values indicating areas where less precipitation is expected to infiltrate the surface, resulting in increased runoff (Table 2-10).

**Table 2-10 Curve Numbers for U.S Virgin Islands land use classes.**

| ***Hydrologic Soil Group*** | **HD Urban** | **LD Urban** | **Dev. Open Space** | **Agriculture** | **Forest & Shrub** | **Wetland** | **Barren** | **Water** |
|---|---|---|---|---|---|---|---|---|
| **A** | 89 | 61 | 49 | 72 | 30 | 0 | 77 | 0 |
| **B** | 92 | 75 | 69 | 81 | 55 | 0 | 86 | 0 |
| **C** | 94 | 83 | 79 | 88 | 70 | 0 | 91 | 0 |
| **D** | 95 | 87 | 84 | 91 | 77 | 0 | 94 | 0 |

L-THIA calculates runoff depth for each storm event and each curve number throughout the period of the available precipitation record. The average annual runoff depths are then multiplied by the area represented by that curve number to determine an average runoff volume. The GIS version of L-THIA completes these calculations within discrete grid cells, which facilitates the aggregation and reporting of runoff volumes from larger spatial units, such as the 14-digit hydrologic units used in this analysis.

Pollutant loading is calculated within L-THIA using an event mean concentration (EMC) method. EMC values were initially compiled by the Texas Natural Resource Conservation Commission (Baird & Jennings, 1996). Over time, EMC values have been adjusted using flow averaged samples to account for variations (typically decreases) in pollutant concentration that occur during prolonged rain events. L-THIA calculates annual pollutant volume by multiplying these flow-averaged EMC values by the annual runoff volumes.

For the USVI analysis, soils, land use, and precipitation data were acquired from publicly available sources (Table 2-11). L-THIA requires the use of a single precipitation data set. To account for differences in the precipitation record among islands, a unique precipitation data set was used for each island for the period 1981-2009 (29 years). The default (normal) antecedent soil moisture condition within L-THIA was selected for all analyses. Total fecal coliform loadings were calculated using the runoff volumes calculated by L-THIA and land-use specific EMC values (Engel, Choi, & Theller, 2010), reported in CFU/100 mL (Table 2-12).

**Table 2-11 Data sources used for USVI L-THIA runoff analysis.**

| Data | Data Source |
|---|---|
| Soils (hydrologic soil group) | Natural Resources Conservation Service |
| Land Use | USGS Landsat Archive (1992, 2001)<br>NOAA Coastal Change Analysis Program ( 2007) |
| Precipitation (1981-2009) | National Climatic Data Center (COOP-ID):<br>St. Croix – Christiansted Airport (670198)<br>St. John – Coral Bay (671790)<br>St. Thomas – Wintberg (679450) |

**Table 2-12 EMC values for USVI L-THIA fecal coliform analysis.**

| | HD Urban | LD Urban | Dev. Open Space | Agriculture | Forest & Shrub | Wetlan d | Barre n | Wate r |
|---|---|---|---|---|---|---|---|---|
| **Fecal Coliform Event Mean Concentration (# / 100mL)** | 2,000 | 2,000 | 2,000 | 2,600 | 20 | 0 | 2,000 | 0 |

To evaluate differences in runoff and coliform loading resulting from land use changes and precipitation differences across the islands, a total of nine L-THIA analyses were performed (three islands x three time periods). Results are presented in relative terms only because inland water quality data are not available for model calibration (Table 2-13 and Figure 2-5 through Figure 2-7). The relative comparisons presented here are useful for prioritizing future water quality monitoring and management activities. Estimates of annual runoff generated by L-THIA vary among the islands and are generally related to the presence of urban areas (impervious land cover). A comparison of the 1992 and 2001 estimates show generally stable runoff, with slight declines resulting from the presence of vegetation in 2001 over areas that were barren in 1992. This slight decrease in the midst of population increases may be the result of construction of urban and developed open space areas evident in the 2001 imagery. Between 2001 and 2007, significant increases in runoff are predicted by the model. These correspond to the observed decreases in forest and grassland cover and increases in developed open space. Overall, the island of St. Thomas is shown to have the largest increase in runoff (21%) from 2001 to 2007, which is driven by changes in the northern two HUC units. St. John is also shown to have significant increases in runoff, though the absolute values predicted by the model are considerably lower than those predicted for the other islands. This is consistent with the lower population and lower level of urbanization on St. John.

**Table 2-13 Change in annual runoff.**

| HUC | Change in Runoff | |
|---|---|---|
| | 1992-2001 | 2001-2007 |
| ***U.S. Virgin Islands*** | ***-2%*** | ***9%*** |
| ***St. Croix*** | ***-3%*** | ***3%*** |
| Northwest St. Croix (21020002010010) | 1% | 9% |
| Northcentral St. Croix (21020002010020) | 1% | 19% |
| Northeast St. Croix (21020002010030) | -19% | 1% |
| Southeast St. Croix (21020002020010) | -7% | -10% |
| Southparts St. Croix (21020002020020) | 1% | 1% |
| Airport St. Croix (21020002020030) | 9% | 5% |
| Southwest St. Croix (21020002020040) | -3% | 4% |
| ***St. John*** | ***-4%*** | ***13%*** |
| North St. John (21020001020010) | -3% | 10% |
| Southeast St. John (21020001020020) | -6% | 7% |
| Southwest St. John (21020001020030) | -2% | 21% |
| ***St. Thomas*** | ***-1%*** | ***21%*** |
| Northwest St. Thomas (21020001010010) | 2% | 46% |
| Northeast St. Thomas (21020001010020) | 2% | 40% |
| Southeast St. Thomas (21020001010030) | -1% | 13% |
| Southwest St. Thomas (21020001010040) | -3% | 9% |

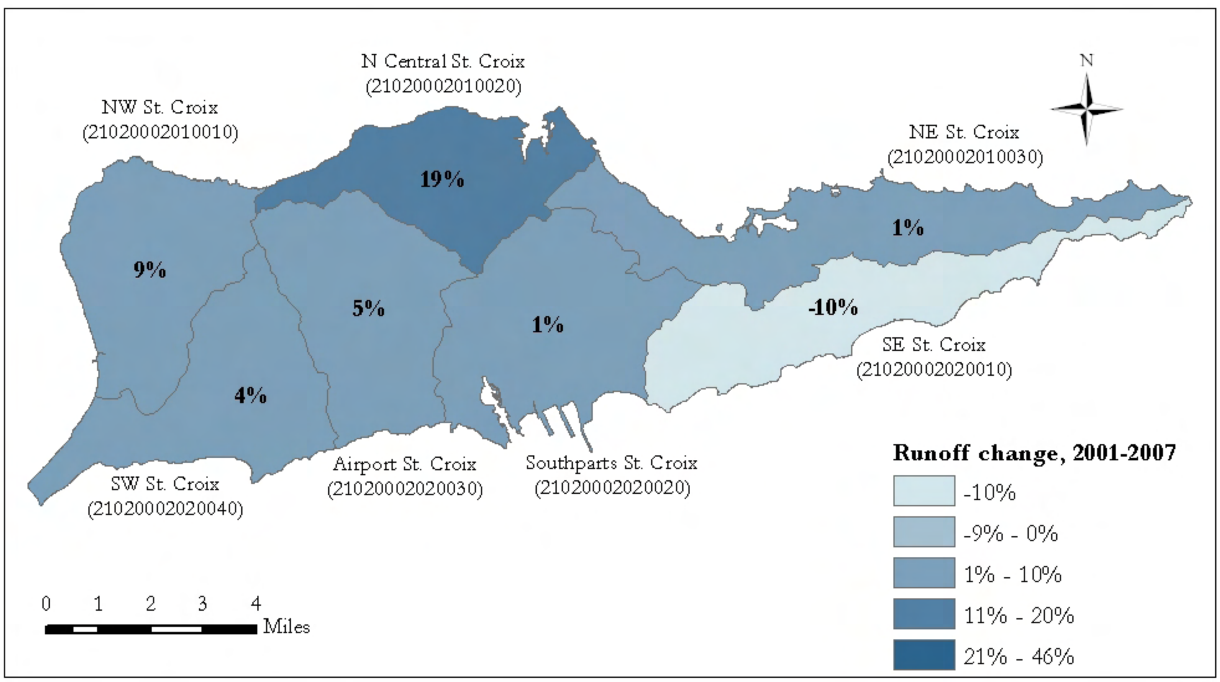



**Figure 2-5 Estimated change in runoff on St. Croix, 2001-2007 land use.**

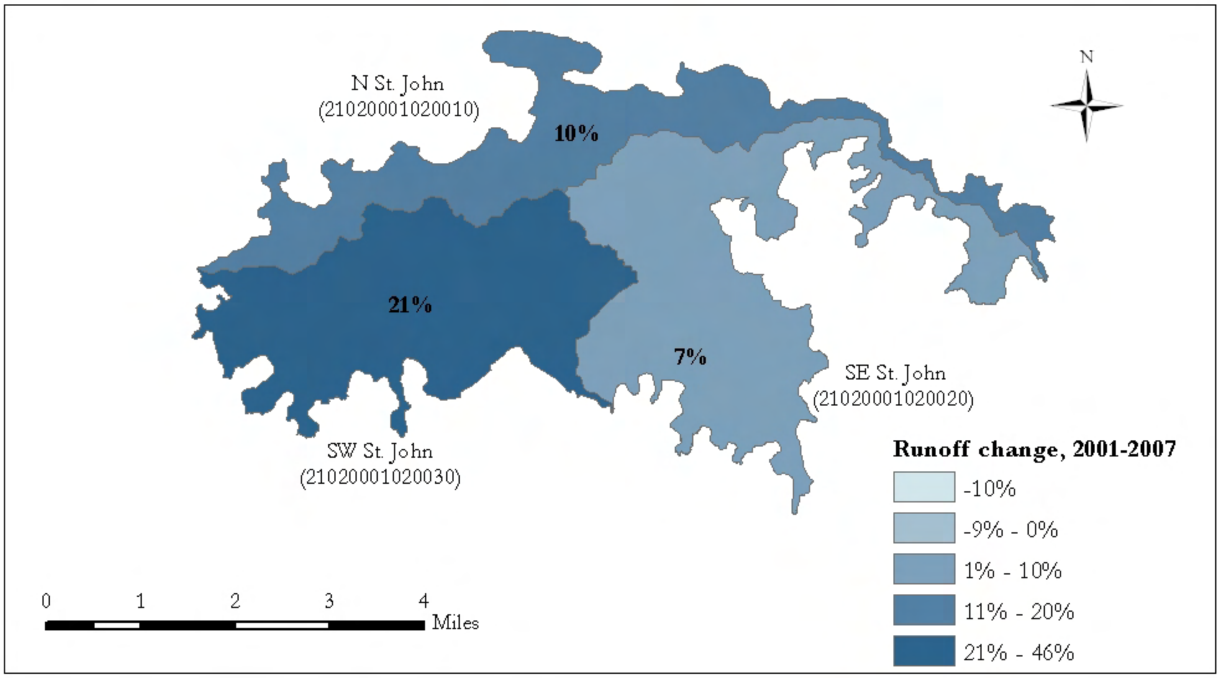



**Figure 2-6 Estimated change in runoff on St. John, 2001-2007 land use.**

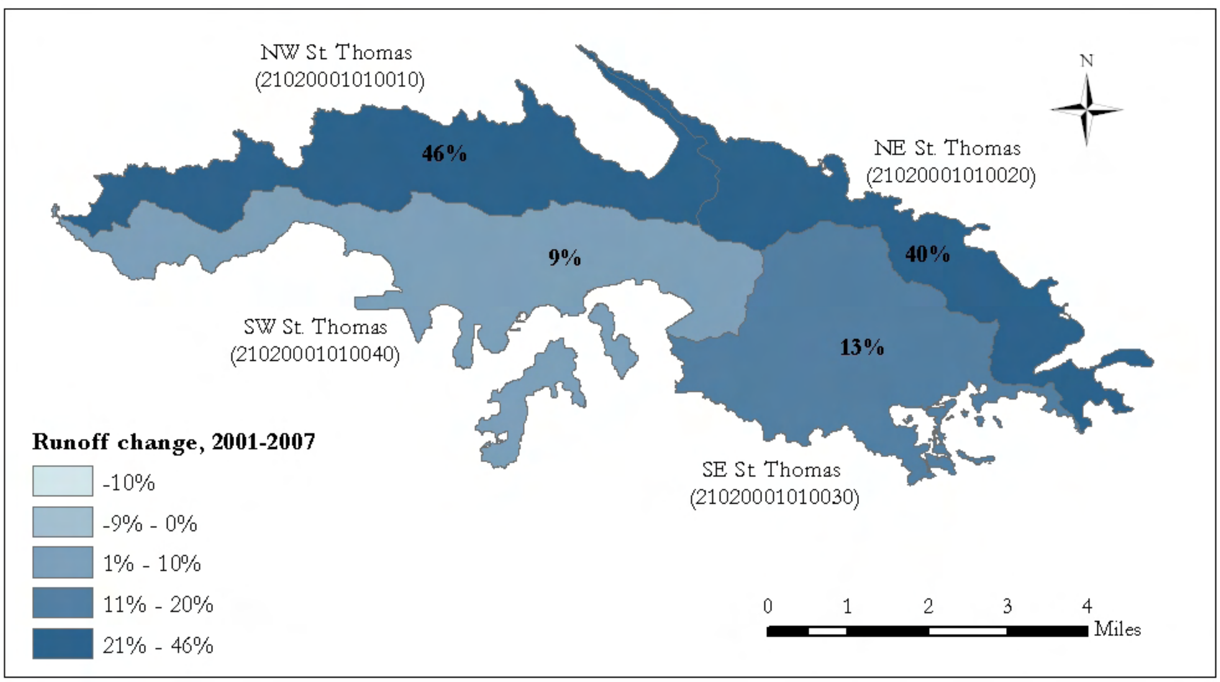



**Figure 2-7 Estimated change in runoff on St. Thomas, 2001-2007 land use.**

Estimated fecal coliform yields follow a pattern that is similar to runoff. It is important to note that model results for fecal coliform are highly sensitive to changes in land use because the EMC values vary by more than two orders of magnitude. These results underscore the importance of the relationship between impervious cover, runoff, and pathogen loading. In areas where runoff was estimated to increase significantly, changes in fecal coliform loading were magnified. Estimates of fecal coliform loading generated by L-THIA vary among the islands, and are most prevalent in Northeast St. Croix (Figure 2-8 to Figure 2-10). Changes in fecal coliform loading over time are displayed in Table 2-14 and Figure 2-11 to Figure 2-13. The less populated and less urbanized island of St. John has the lowest coliform yields in the USVI, although the sharp percentage increases, likely due to increased urbanization, are noteworthy.

**Table 2-14 Annual change in fecal coliform loading.**

| HUC | Change in fecal coliform loading | |
|---|---|---|
| | **1992-2001** | **2001-2007** |
| ***U.S. Virgin Islands*** | ***-5%*** | ***24%*** |
| ***St. Croix*** | ***-6%*** | ***11%*** |
| Northwest St. Croix (21020002010010) | 3% | 134% |
| Northcentral St. Croix (21020002010020) | -2% | 81% |
| Northeast St. Croix (21020002010030) | -34% | 4% |
| Southeast St. Croix (21020002020010) | -16% | -32% |
| Southparts St. Croix (21020002020020) | 3% | 1% |
| Airport St. Croix (21020002020030) | 48% | 24% |
| Southwest St. Croix (21020002020040) | -10% | 14% |
| ***St. John*** | ***-10%*** | ***82%*** |
| North St. John (21020001020010) | -46% | 391% |
| Southeast St. John (21020001020020) | -10% | 18% |
| Southwest St. John (21020001020030) | -2% | 135% |
| ***St. Thomas*** | ***1%*** | ***43%*** |
| Northwest St. Thomas (21020001010010) | 36% | 507% |
| Northeast St. Thomas (21020001010020) | 16% | 98% |
| Southeast St. Thomas (21020001010030) | 1% | 17% |
| Southwest St. Thomas (21020001010040) | -4% | 15% |

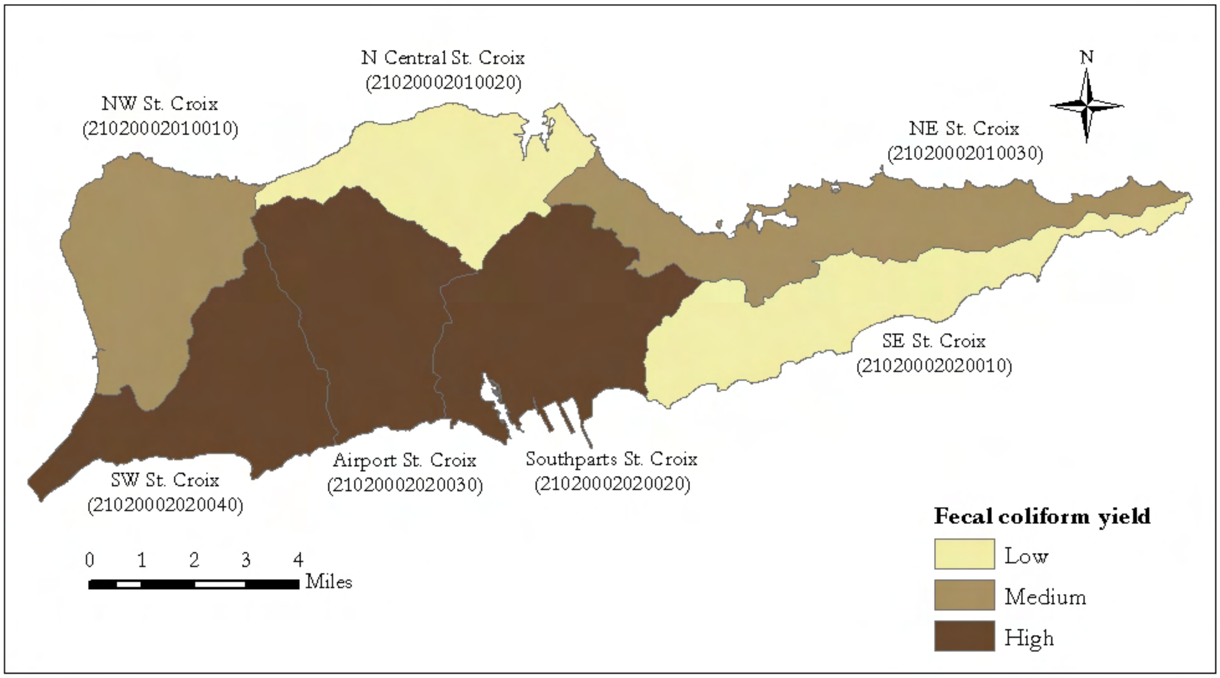



**Figure 2-8 Estimated fecal coliform yield on St. Croix, based on 2007 land use. The Low, Medium, and High yield categories represent quantiles for relative comparison purposes.**

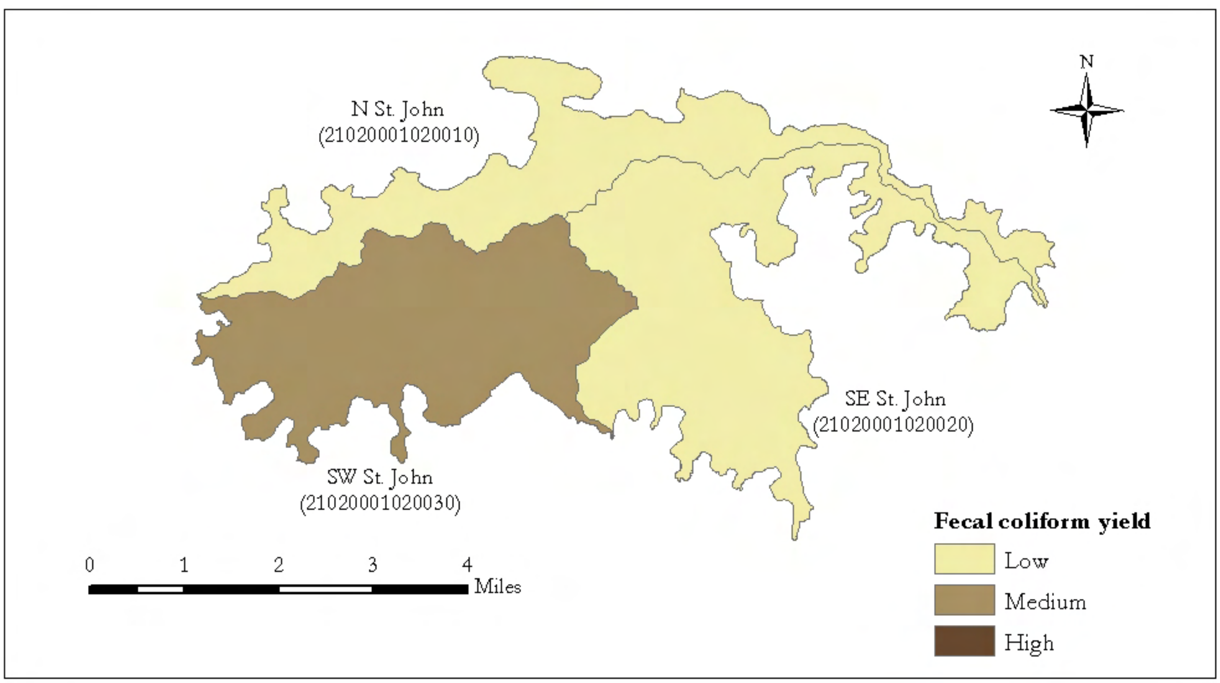



**Figure 2-9 Estimated fecal coliform yield on St. John, based on 2007 land use. The Low, Medium, and High yield categories represent quantiles for comparison purposes.**

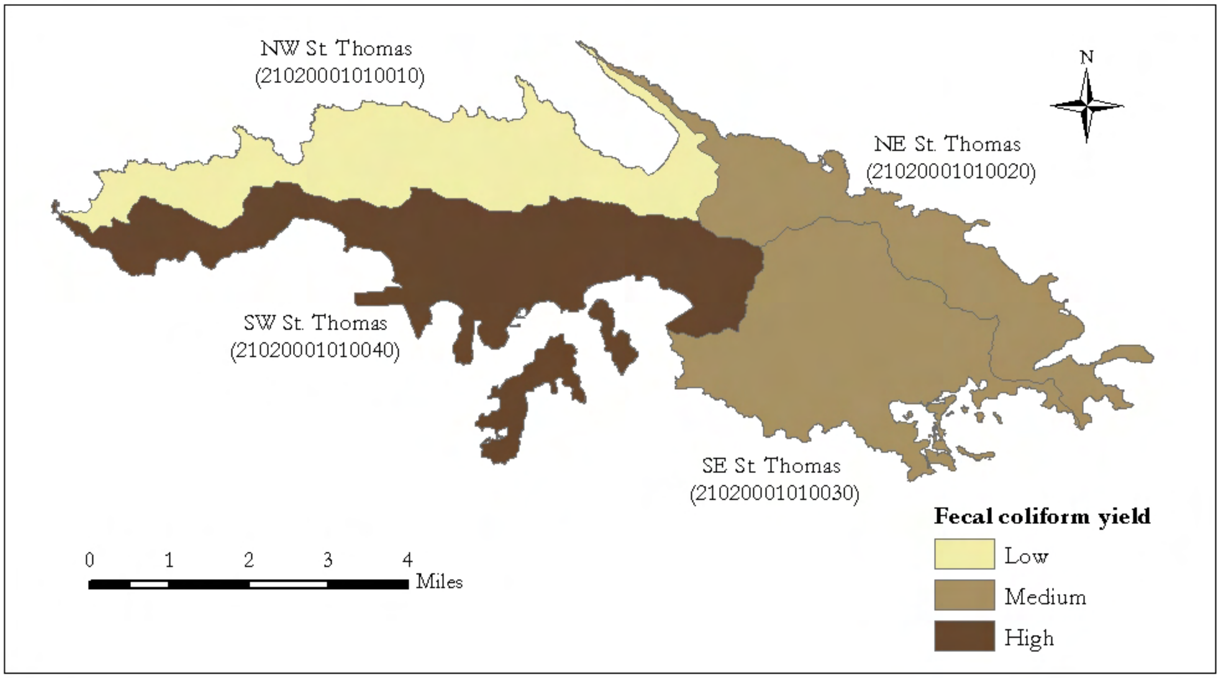



**Figure 2-10 Estimated fecal coliform yield on St. Thomas, based on 2007 land use. The Low, Medium, and High yield categories represent quantiles for comparison purposes.**

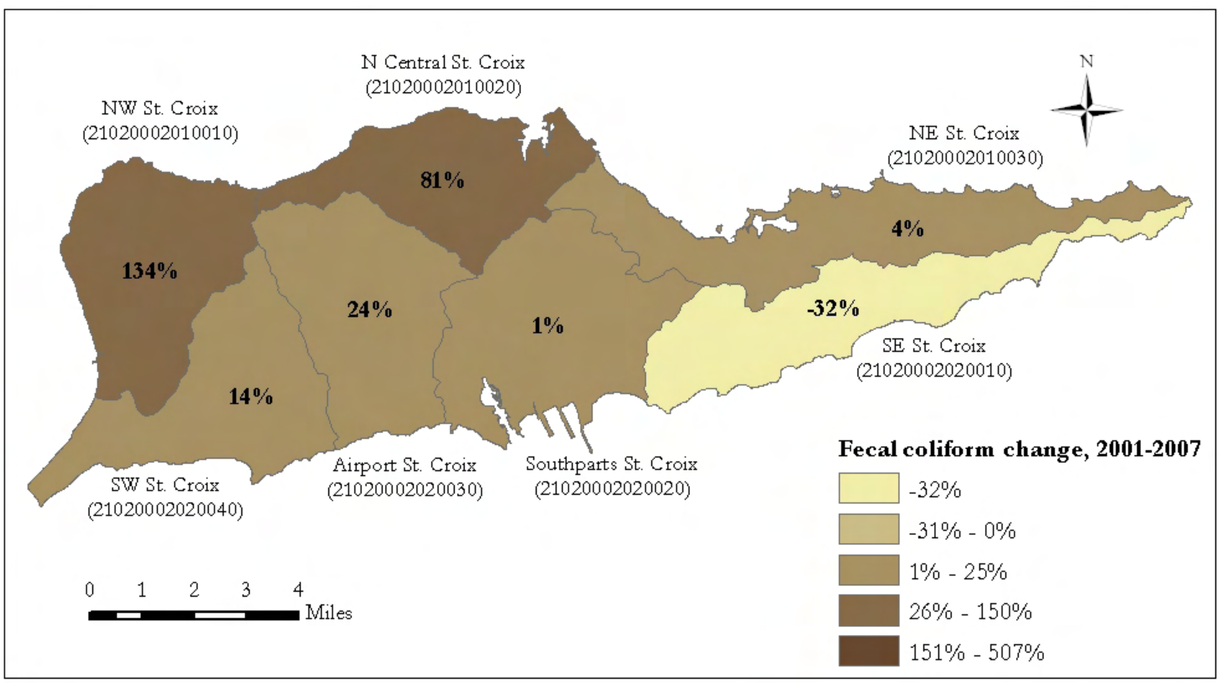



**Figure 2-11 Estimated change in fecal coliform yield on St. Croix, 2001-2007 land use.**

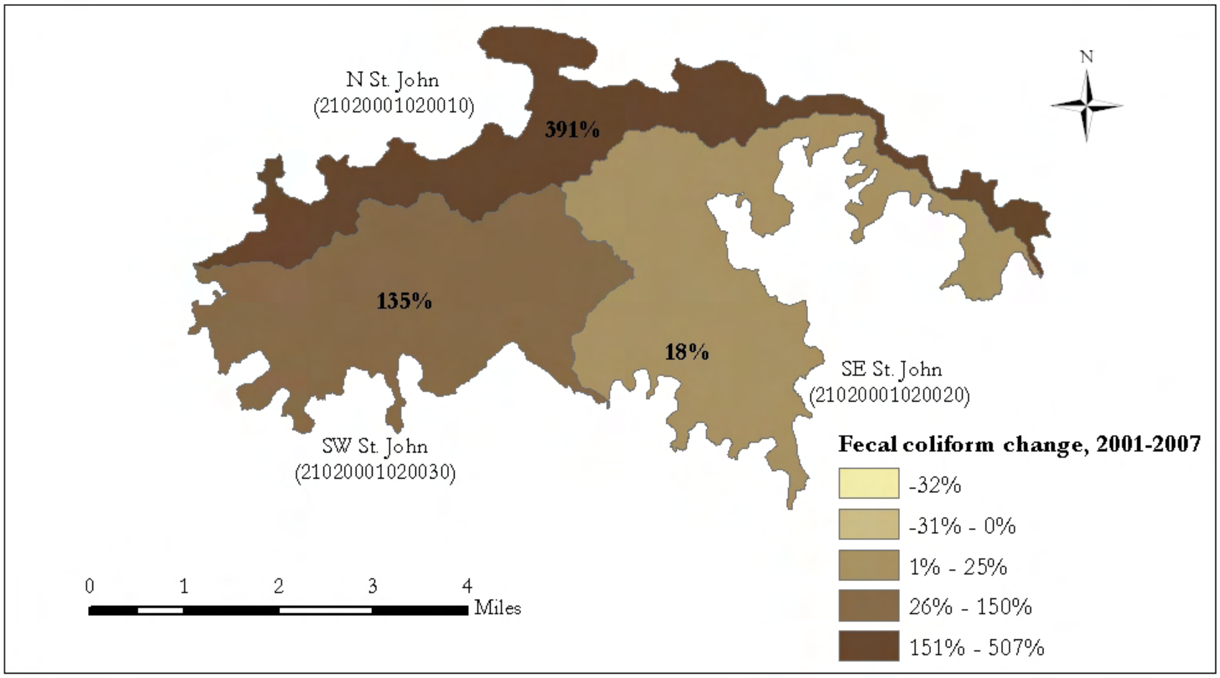



**Figure 2-12 Estimated change in fecal coliform yield on St. John, 2001-2007 land use.**

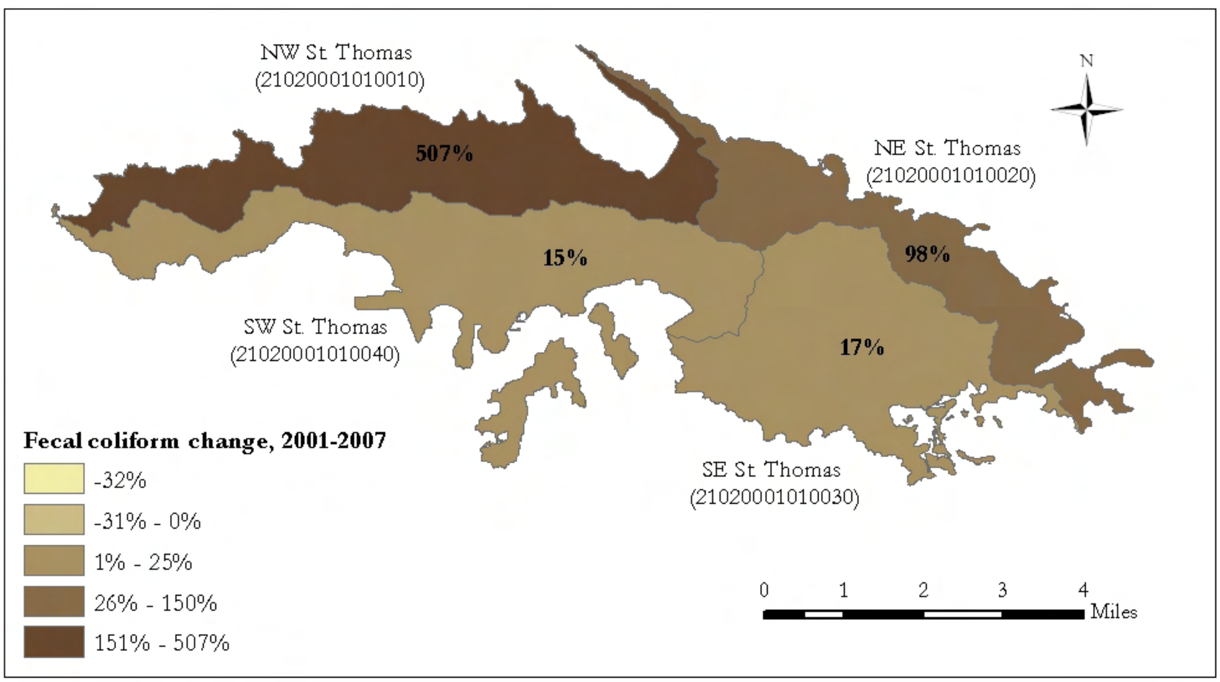



**Figure 2-13 Estimated change in fecal coliform yield on St. Thomas, 2001-2007 land use.**

## 2.4 Trends in Coastal Pathogen Data

Changes in water quality over time are often related to concurrent changes in land use, climate, or point source discharges to a water body. Water quality trend analyses are useful for evaluating changes over time and in the context of these related variables. They are particularly useful when used in conjunction with land use trend analyses to inform watershed planning.

Trends in USVI coastal water quality data were assessed to identify significant changes in pathogen contamination since 2000. Water quality data collected for USVI coastal waters over the period of January 1, 2000 through December 31, 2009 were obtained from the U.S. EPA STORET database (U.S. Environmental Protection Agency, 2009). During this period, pathogen monitoring in USVI waters was conducted through measurement of multiple pathogen indicators (fecal coliform, enterococcus, and E. coli). Measurements were not collected with regular frequency over the entire length of the monitoring period for any indicator. The indicator with the most complete data record is fecal coliform, and all trend analysis was completed using the fecal coliform dataset.

Trend analysis was applied to data collected at 157 coastal water quality monitoring stations, which are distributed throughout the islands (Figure 2-14, Figure 2-15, and Figure 2-16). Trend analysis was limited to monitoring stations located near the coastlines of St. Croix, St. John, and St. Thomas; data from offshore stations was excluded. Water quality samples were collected quarterly at all monitoring stations. However, results from a number of quarters were missing from the dataset, and no results from the period of January 1, 2006 through December 31, 2007 were available.

Fecal coliform data were processed by removing individual samples with unreported results. Samples identified as quality control samples (those taken at the same time and location as another sample) were also removed. Fecal coliform concentration was reported as greater than the upper detection limit for 7 samples. Fecal coliform concentration for these samples was estimated as the maximum reported value in the dataset (3,760 colony forming units (CFU) per 100 mL). Data from monitoring stations with fewer than 16 sample records were not considered in trend analysis. Cleaned data included a total of 2,476 samples from 111 monitoring stations.

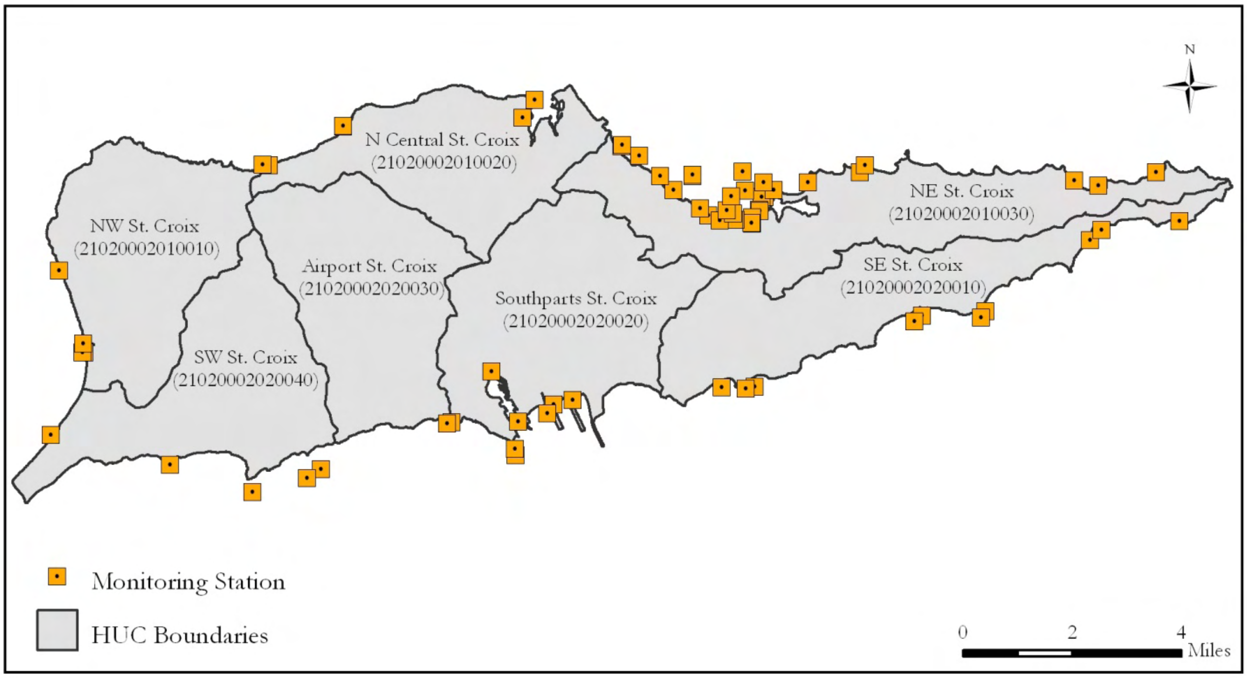



**Figure 2-14 Location of St. Croix fecal coliform monitoring stations included in trend analysis.**

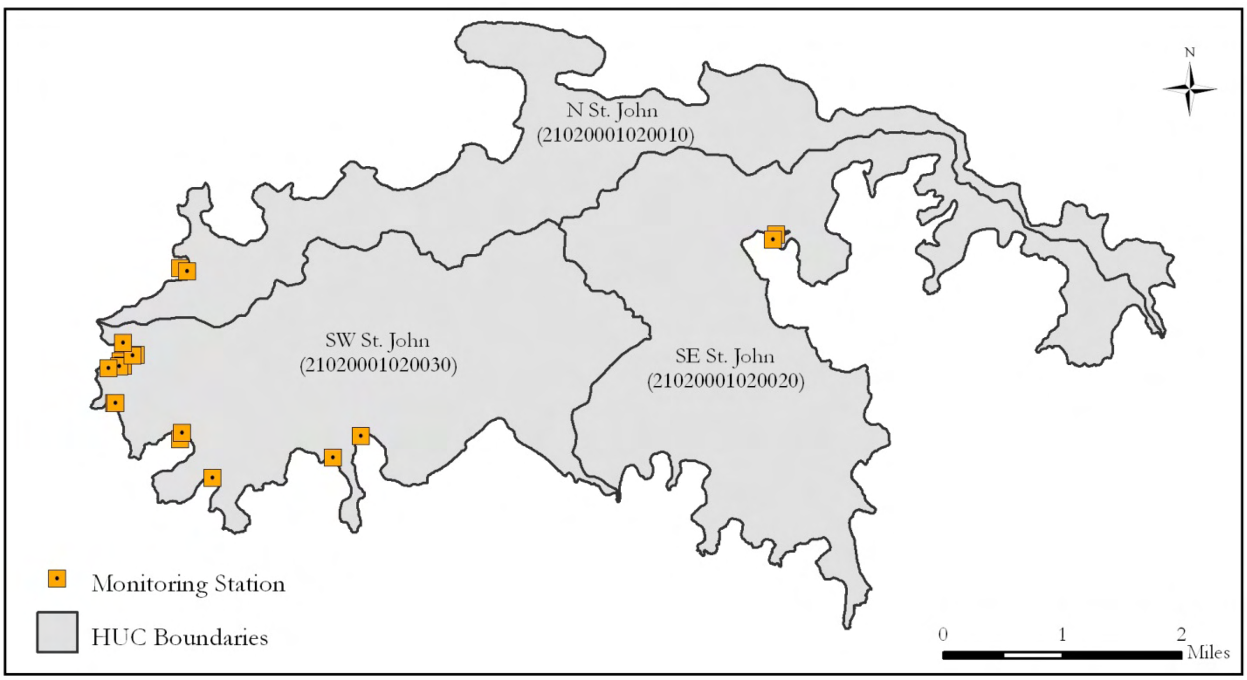



**Figure 2-15 Location of St. John fecal coliform monitoring stations included in trend analysis.**

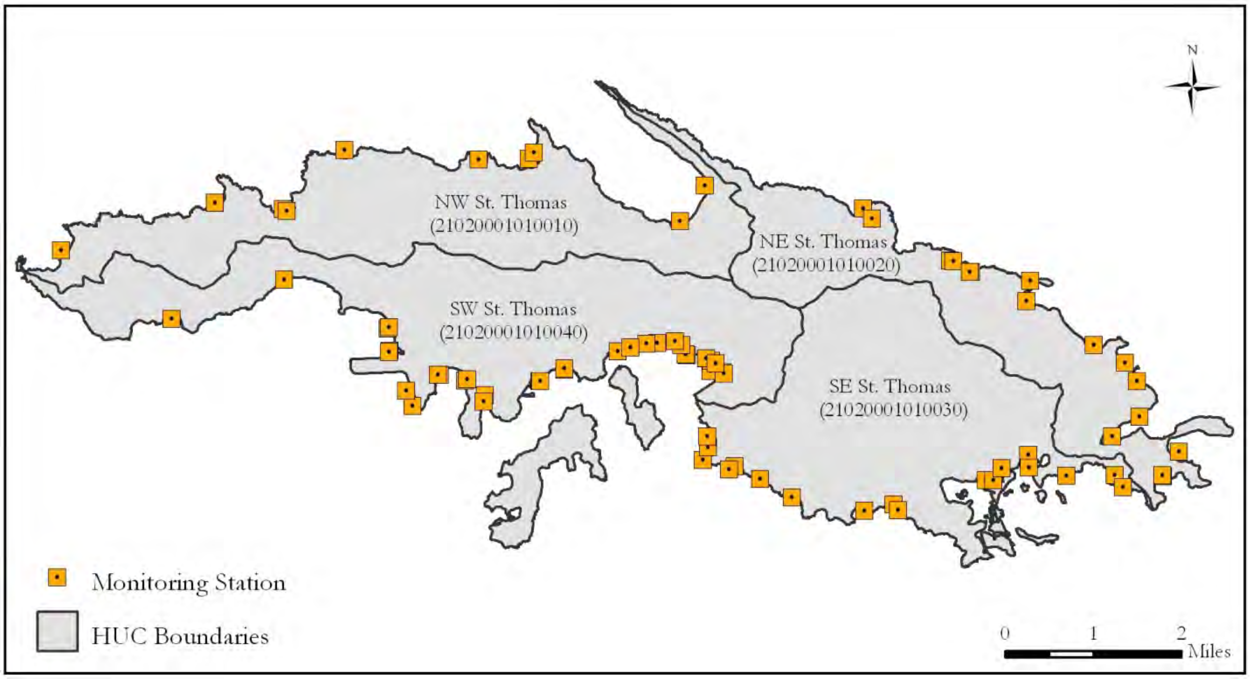



**Figure 2-16 Location of St. Thomas fecal coliform monitoring stations included in trend analysis.**

Statistical analysis of fecal coliform time series data was carried out through application of the Regional Kendall (RK) test for trend (Helsel & Frans, 2006). The RK test was selected for multiple reasons. First, the RK test includes no assumption of a normally distributed dependent variable. The distribution of fecal coliform data is highly non-normal, thus use of a non-parametric test is required unless the dataset is transformed. Second, the RK test is relatively insensitive to missing data points, which is ideal in this case because it is known that the samples in this dataset were taken at irregular time intervals. Finally, the RK test uses results of the Mann-Kendall test for trend from individual sampling sites to identify a trend across a region. Here, trends were evaluated for USVI watersheds and major islands. The identity of the nearest 14-digit hydrologic unit and island was assigned to each monitoring station, and the RK test was applied to monitoring station groups using the USGS computer program for the Kendall family of trend tests (Helsel D. R., 2006). Select watersheds (North St. John, Southeast St. John, and Northeast St. Croix) contained one monitoring station only. Trend analysis for these watersheds was based on Mann-Kendall test results for their respective single stations.

Table 2-15 summarizes fecal coliform data by 14-digit HUC and island. The low geometric mean of observed fecal coliform concentrations for each HUC and island (0-1 CFU/100 mL) is a product of the large proportion of samples reported to contain no fecal coliform colonies (concentration reported as 0 CFU/100 mL). Figure 2-17 illustrates reported fecal coliform concentrations from a typical monitoring station (based on the number of observations and concentration range/variability). The majority of samples collected at this station are reported to contain 0 CFU/100 mL (illustrated as 0.1 CFU/100 mL in Figure 2-17 to display on semi-log plot), with non-zero concentrations spanning multiple orders of magnitude. These data were confirmed with the USVI DPNR (personal communication, May 24, 2010).

**Table 2-15 Summary of fecal coliform monitoring data for each 14-digit Hydrologic Unit Code (HUC) and island.**

| HUC/Island | # of Stations | # Of Samples | Mean Concentration[1] (CFU/100 mL) | Standard Deviation[2] (CFU/100 mL) |
|---|---|---|---|---|
| ***St. Croix*** | **49** | **1149** | **1** | **8** |
| Northwest St. Croix (21020002010010) | 3 | 66 | 0 | 10 |
| Northcentral St. Croix (21020002010020) | 4 | 80 | 0 | 8 |
| Northeast St. Croix (21020002010030) | 25 | 590 | 0 | 6 |
| Southeast St. Croix (21020002020010) | 5 | 142 | 0 | 2 |
| Southparts St. Croix (21020002020020) | 7 | 149 | 0 | 5 |
| Airport St. Croix (21020002020030) | 1 | 25 | 0 | 4 |
| Southwest St. Croix (21020002020040) | 4 | 97 | 0 | 1 |
| ***St. John*** | **11** | **228** | **1** | **9** |
| North St. John (21020001020010) | 1 | 17 | 1 | 6 |
| Southeast St. John (21020001020020) | 1 | 16 | 1 | 6 |
| Southwest St. John (21020001020030) | 9 | 195 | 1 | 9 |
| ***St. Thomas*** | **51** | **1099** | **1** | **8** |
| Northwest St. Thomas (21020001010010) | 8 | 181 | 0 | 4 |
| Northeast St. Thomas (21020001010020) | 13 | 278 | 0 | 6 |
| Southeast St. Thomas (21020001010030) | 13 | 259 | 1 | 11 |
| Southwest St. Thomas (21020001010040) | 17 | 381 | 1 | 8 |

[1] Geometric mean (samples with fecal coliform concentration reported as 0 CFU/100 mL changed to 0.1 CFU/100 mL for geometric mean calculations)

[2] Geometric standard deviation (samples with fecal coliform concentration reported as 0 CFU/100 mL changed to 0.1 CFU/100 mL for geometric standard deviation calculations)

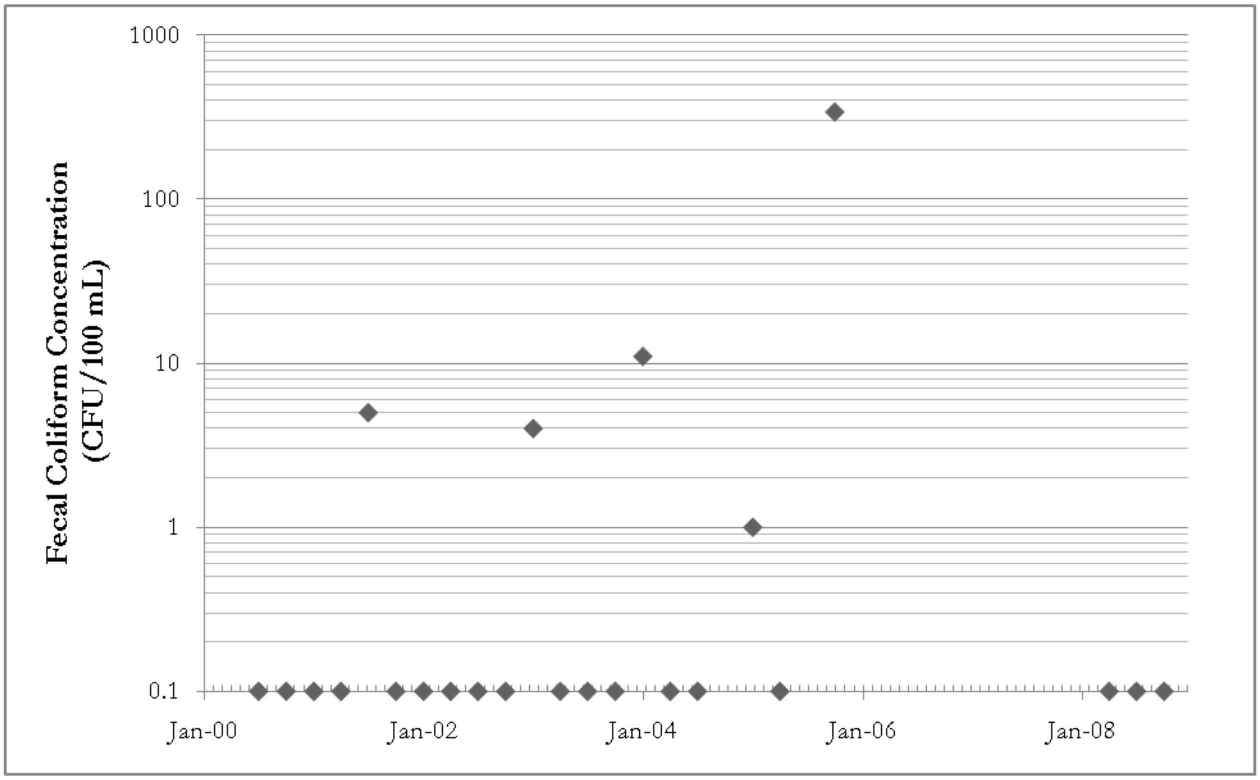



**Figure 2-17 Fecal coliform time series from St. Croix Water and Power Authority intake monitoring station (Station ID STC-46). Note that measured values of 0 CFU/100 mL are represented as 0.1 CFU/100 mL to display on semi-log plot.**

Table 2-16 presents results of the trend analysis. A statistically-significant trend of increasing fecal coliform concentration since 2000 was identified for 3 of 14 watersheds (at $p < 0.05$). However, the estimated rate of change in fecal coliform concentration over the period of analysis was minimal for these watersheds (increase of < 0.005 CFU/100 mL/year). Similar results were found among islands. A statistically-significant positive trend was identified for St. Croix and St. John. The estimated annual concentration change associated with these trends was minimal (increase of < 0.005 CFU/100 mL/year). Results indicate that while pathogen contamination may be becoming more prevalent in select areas of the USVI, the overall rate of increase is minor.

Fecal coliform trend analysis should be interpreted with the understanding that results may be skewed by a number of factors. The irregular collection frequency of water quality samples and large gap in the dataset from 2006-2007 likely affect the accuracy of trend detection. Changes in sampling location are also of concern; a number of stations reported shifts in collection latitude/longitude in post-2007 samples. Furthermore, trend analysis does not account for external influences which may vary randomly from one sample date to the next, such as recent rainfall and runoff driven nonpoint source loading. The following section explores these and other potential influences on measured fecal coliform concentrations.

**Table 2-16 Results of fecal coliform trend analysis for each 14-digit Hydrologic Unit Code (HUC) and island.**

| HUC/Island | Annual Change in Concentration (CFU/100 mL/year) | p-value |
|---|---|---|
| ***St. Croix*** | **<0.005** | **0.02*** |
| Northwest St. Croix (21020002010010) | <0.005 | 0.07 |
| Northcentral St. Croix (21020002010020) | <0.005 | 0.95 |
| Northeast St. Croix (21020002010030) | <0.005 | <0.001* |
| Southeast St. Croix (21020002020010) | <0.005 | 0.36 |
| Southparts St. Croix (21020002020020) | <0.005 | 0.48 |
| Airport St. Croix (21020002020030) | <0.005 | 0.18 |
| Southwest St. Croix (21020002020040) | <0.005 | 0.52 |
| ***St. John*** | **<0.005** | **0.57** |
| North St. John (21020001020010) | -3.3 | 0.39 |
| Southeast St. John (21020001020020) | <0.005 | 0.19 |
| Southwest St. John (21020001020030) | <0.005 | 0.71 |
| ***St. Thomas*** | **<0.005** | **<0.001*** |
| Northwest St. Thomas (21020001010010) | <0.005 | 0.01* |
| Northeast St. Thomas (21020001010020) | <0.005 | <0.001* |
| Southeast St. Thomas (21020001010030) | <0.005 | 0.11 |
| Southwest St. Thomas (21020001010040) | <0.005 | 0.13 |

* Trend significant at $p < 0.05$

## 2.5 Pathogen Water Quality Standard Exceedance

USVI Class B water quality standard regulations state that the concentration of fecal coliform in USVI waters must not exceed 70 CFU/100mL (Virgin Islands Department of Planning and Natural Resources, 2010). Approximately 2% of coastal water quality samples collected from January 1, 2000 through December 31, 2009 (for which fecal coliform was measured) contained fecal coliform concentrations above this threshold. Analysis was undertaken to investigate characteristics shared by these samples so that factors contributing to fecal coliform exceedance could be identified. Sample characteristics considered in exceedance analysis relate to runoff driven nonpoint source loading and proximity to potential sources of fecal coliform contamination:

- Time elapsed since rainfall.
- Distance to nearest stream/gut outlet.
- Distance to nearest point source.
- Distance to nearest marina.

Water quality data used in fecal coliform exceedance analysis included those samples used in trend analysis and samples from monitoring stations with sparse data records (less than 16 observations). Recent rainfall and proximity to potential fecal coliform sources were evaluated for a total of 2,613 samples (2,551 non-exceedance samples, 62 exceedance samples) from 131 water quality monitoring stations. Time elapsed since rainfall was estimated from daily precipitation measurements collected at NCDC weather stations. The weather station with the most complete data record during the period of analysis on each major island was identified and selected for rainfall calculations. Days with rainfall were defined as those in which total daily precipitation was reported as greater than 0.1 inches. Spatial analysis was applied to generate potential source proximity estimates. Stream/gut outlet locations were determined from stream network data generated from 30-meter resolution digital elevation model (DEM) data. Point source locations were determined from U.S. EPA records of permitted fecal coliform point sources in the USVI (U.S. Environmental Protection Agency, 2010). Marina locations were determined from boatyard and marina spatial data provided by The Nature Conservancy (Shawn Margles, personal communication, June 16, 2010). All proximity estimates were calculated as the straight-line distance (in meters) from the reported location of sample collection to the nearest potential pollution source. In addition to the above, the identity of the nearest upstream watershed was determined from reported sample collection locations, the stream/gut network, and 14-digit HUC boundaries. Water quality monitoring station locations and spatial predictors of fecal coliform exceedance are illustrated for each island in Figure 2-18, Figure 2-19, and Figure 2-20.

Table 2-17 summarizes fecal coliform exceedance statistics by HUC. Watersheds with the largest number of samples exceeding the fecal coliform standard were NE St. Croix (12 samples), SW St. Thomas (18 samples), and SE St. Thomas (14 samples). The total number of samples collected in each watershed varied (ranging from 25 in Airport St. Croix to 590 in NE St. Croix). Therefore, the ratio of exceedance samples to total samples is a more useful measure for comparison. Watersheds with the largest exceedance ratio (5%) were SE St. Thomas, SW St. Thomas, and NW St. Croix.

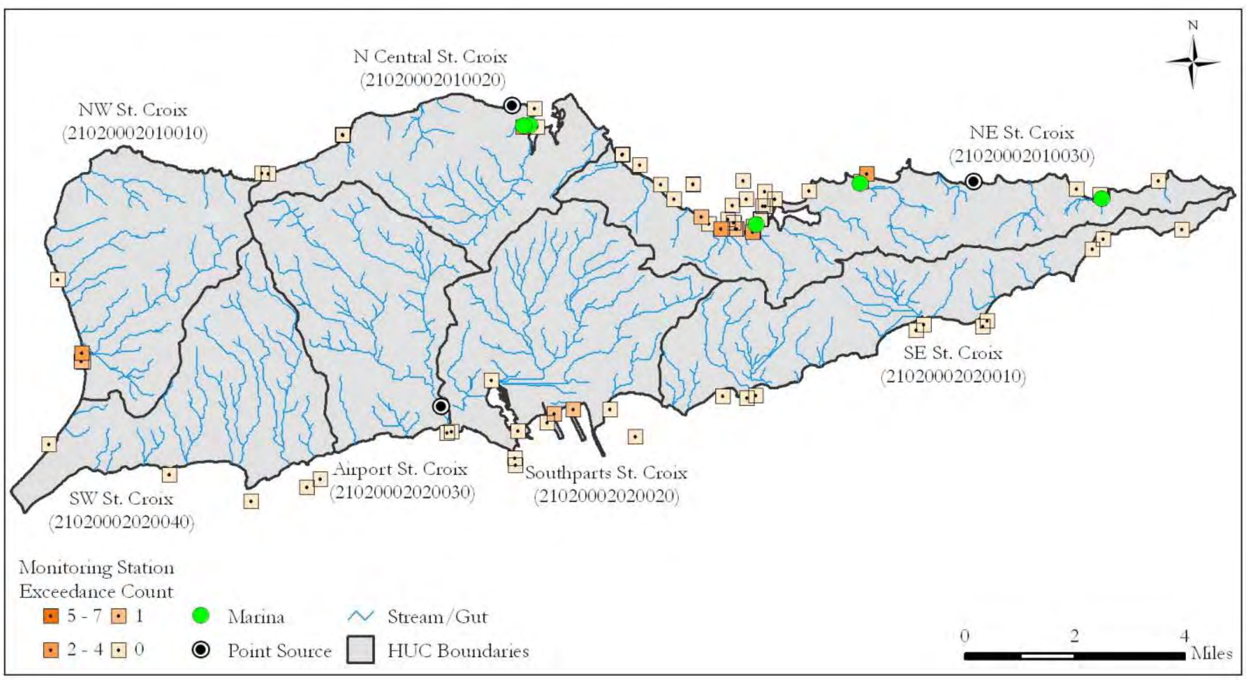



**Figure 2-18 St. Croix fecal coliform monitoring stations and potential sources considered in exceedance analysis.**

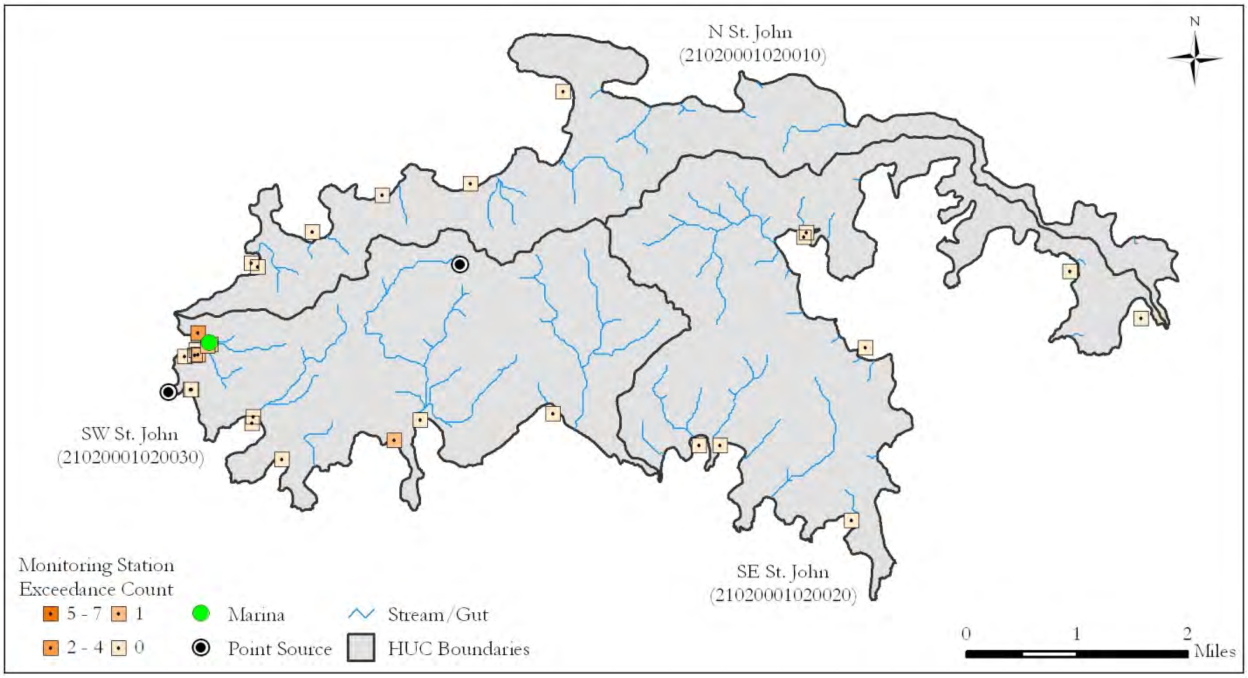



**Figure 2-19 St. John fecal coliform monitoring stations and potential sources considered in exceedance analysis.**

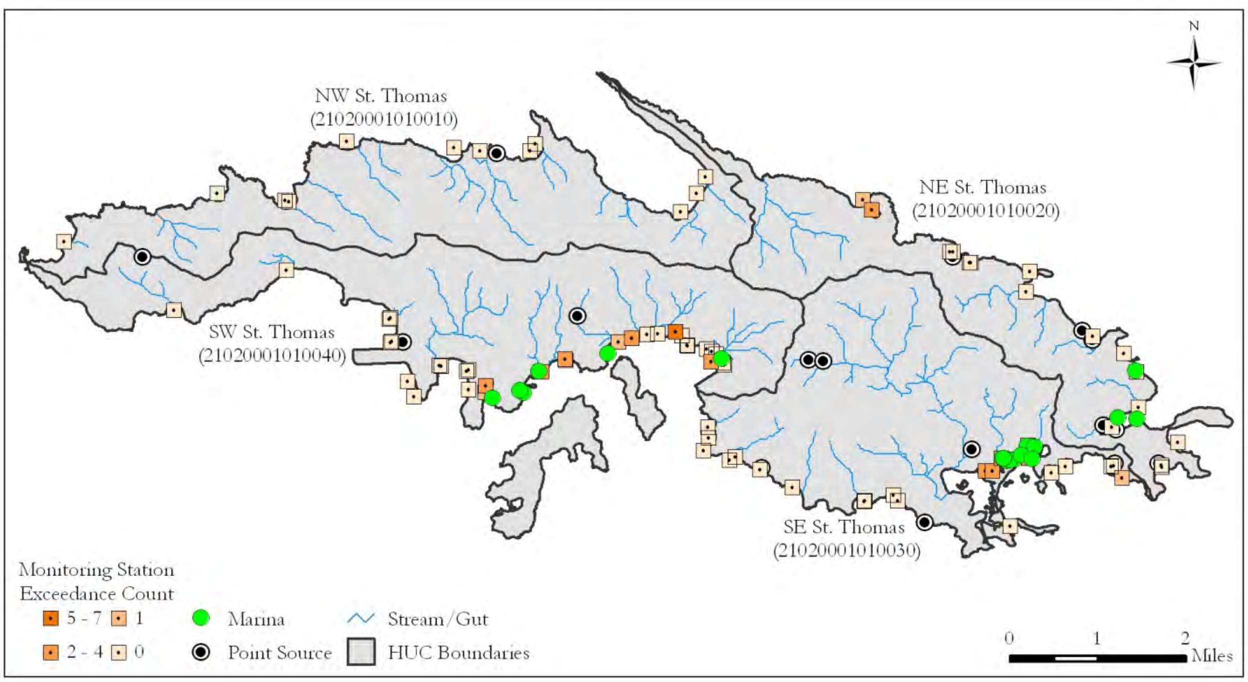



**Figure 2-20 St. Thomas fecal coliform monitoring stations and potential sources considered in exceedance analysis.**

**Table 2-17 Fecal coliform exceedance statistics for each 14-Digit Hydrologic Unit Code (HUC).**

| HUC | Total Samples | Exceedance Samples | Exceedance Ratio |
|---|---|---|---|
| ***St. Croix*** | ***1159*** | ***19*** | ***2%*** |
| Northwest St. Croix (21020002010010) | 66 | 3 | 5% |
| Northcentral St. Croix (21020002010020) | 83 | 2 | 2% |
| Northeast St. Croix (21020002010030) | 590 | 12 | 2% |
| Southeast St. Croix (21020002020010) | 142 | 0 | 0% |
| Southparts St. Croix (21020002020020) | 156 | 2 | 1% |
| Airport St. Croix (21020002020030) | 25 | 0 | 0% |
| Southwest St. Croix (21020002020040) | 97 | 0 | 0% |
| ***St. John*** | ***335*** | ***7*** | ***2%*** |
| North St. John (21020001020010) | 64 | 0 | 0% |
| Southeast St. John (21020001020020) | 66 | 0 | 0% |
| Southwest St. John (21020001020030) | 205 | 7 | 3% |
| ***St. Thomas*** | ***1,119*** | ***36*** | ***3%*** |
| Northwest St. Thomas (21020001010010) | 196 | 0 | 0% |
| Northeast St. Thomas (21020001010020) | 278 | 4 | 1% |
| Southeast St. Thomas (21020001010030) | 263 | 14 | 5% |
| Southwest St. Thomas (21020001010040) | 382 | 18 | 5% |

Fecal coliform exceedance statistics for each potential predictor are summarized in Table 2-18, Table 2-19, Table 2-20, and Table 2-21. To ease illustration and interpretation, results are presented with samples binned into quantiles of the empirical distribution of the predictors (i.e., samples are binned according to the magnitude of the predictors so that each bin contains a similar number of observations). Predictors containing an uneven distribution of exceedance samples among bins include time-since-rainfall, marina distance, and stream outlet distance. A large proportion of samples collected within two days of rainfall exceed the fecal coliform standard relative to those collected during dry conditions (Table 2-18). Stations located near a marina (within 250 meters) generally contain more instances of fecal coliform exceedance than those located further from a marina (Table 2-21). A large number of exceedance samples were collected from monitoring stations located at immediate and intermediate distances to a stream outlet (Table 2-19).

The relationship between individual predictors and fecal coliform exceedance was initially evaluated using the chi-square test of independence. The chi-square test of independence is used to determine the statistical significance of differences between the observed and expected frequencies of event occurrence. Here, the observed number of exceedance samples in predictor bins was compared to the case in which exceedance samples were evenly distributed among bins. Since bins have a similar number of observations, it can be proposed that if the predictor had no effect on exceedance, bins would contain an equal number of exceedance samples. Results of the chi-square test of independence show that exceedance sample distribution significantly differed from equal distribution for 3 predictors; time-since-rainfall ($p$ = 4E-05), stream outlet proximity ($p$ = 6E-06), and marina proximity ($p$ = 9E-09). Exceedance sample distribution did not significantly differ from equal distribution for point source proximity data ($p$ = 0.10). Similar analysis was performed for exceedance counts by watershed, with expected values estimated from the proportion of total samples collected in each watershed. The observed distribution of exceedance samples among watersheds significantly differed from equal distribution (p = 4E-04), indicating that watershed characteristics (e.g., land use) likely influence fecal coliform exceedance in coastal water quality samples.

**Table 2-18 Fecal coliform exceedance statistics for time elapsed since rainfall.**

| Last Rainfall | Total Samples | Exceedance Samples | Exceedance Ratio |
|---|---|---|---|
| 0 days | 480 | 18 | 4% |
| 1 day | 330 | 14 | 4% |
| 2 days | 378 | 14 | 4% |
| 3-7 days | 452 | 4 | 1% |
| 8-14 days | 461 | 8 | 2% |
| 15-30 days | 370 | 4 | 1% |
| 31-44 days | 142 | 0 | 0% |

**Table 2-19 Fecal coliform exceedance statistics for nearest stream outlet distance.**

| Stream Outlet Distance | Total Samples | Exceedance Samples | Exceedance Ratio |
|---|---|---|---|
| 15-80 meters | 263 | 10 | 4% |
| 81-130 meters | 261 | 3 | 1% |
| 131-185 meters | 270 | 6 | 2% |
| 186-246 meters | 256 | 4 | 2% |
| 247-340 meters | 254 | 18 | 7% |
| 341-495 meters | 255 | 11 | 4% |
| 496-610 meters | 260 | 2 | 1% |
| 611-785 meters | 249 | 1 | 0% |
| 786-1185 meters | 259 | 3 | 1% |
| 1186-4120 meters | 286 | 4 | 1% |

**Table 2-20 Fecal coliform exceedance statistics for nearest point source distance.**

| Point Source Distance | Total Samples | Exceedance Samples | Exceedance Ratio |
|---|---|---|---|
| 30-486 meters | 258 | 10 | 4% |
| 487-900 meters | 255 | 7 | 3% |
| 901-1445 meters | 261 | 8 | 3% |
| 1446-2000 meters | 258 | 11 | 4% |
| 2000-2850 meters | 271 | 6 | 2% |
| 2851-4110 meters | 255 | 2 | 1% |
| 4111-5100 meters | 263 | 4 | 2% |
| 5101-6630 meters | 266 | 4 | 2% |
| 6631-8000 meters | 254 | 8 | 3% |
| 8001-16000 meters | 272 | 2 | 1% |

**Table 2-21 Fecal coliform exceedance statistics for nearest marina distance.**

| Marina Distance | Total Samples | Exceedance Samples | Exceedance Ratio |
|---|---|---|---|
| 0-20 meters | 255 | 19 | 7% |
| 21-250 meters | 252 | 15 | 6% |
| 251-650 meters | 257 | 7 | 3% |
| 651-900 meters | 255 | 7 | 3% |
| 901-1600 meters | 262 | 4 | 2% |
| 1601-2500 meters | 254 | 0 | 0% |
| 2501-3500 meters | 251 | 1 | 0% |
| 3501-5050 meters | 266 | 4 | 2% |
| 5051-8200 meters | 253 | 2 | 1% |
| 8201-16685 meters | 308 | 3 | 1% |

Potential predictors of fecal coliform exceedance were further examined with logistic regression. Like linear regression, logistic regression estimates the linear relationship between a dependent variable and one or more independent variables. While linear regression relies on the ability to observe the full continuum of possible values that can be taken by the dependent variable, logistic regression is appropriate when the analyst can only observe whether the dependent variable is above or below a threshold (here the presence or absence of fecal coliform exceedance in water quality samples). Logistic regression was applied to fecal coliform exceedance data with all four potential predictors considered. Results are summarized in Table 2-22 and indicate that for all predictors, the probability of exceedance decreases as predictor magnitude increases (i.e., negative parameter estimates). The significance of each potential predictor was assessed with a simple Wald test. Significant predictors of exceedance included time-since-rainfall ($p = 0.002$) and nearest marina distance ($p = 0.002$) at $p < 0.05$ and also included point source distance ($p = 0.07$) at $p < 0.10$.

**Table 2-22 Summary of logistic regression results for regression without (a) and with (b) recent rainfall*stream outlet distance interaction term.**

| Predictor | a) Without Interaction | | b) With Interaction | |
|---|---|---|---|---|
| | Regression Coefficient | p-value | Regression Coefficient | p-value |
| Time Elapsed Since Rainfall | -7.60E-02 | 0.002** | -2.10E-02 | 0.527 |
| Nearest Stream Outlet | -4.93E-04 | 0.131 | -4.51E-05 | 0.898 |
| Nearest Point Source | -8.48E-05 | 0.070* | -8.72E-05 | 0.063* |
| Nearest Marina | -1.89E-04 | 0.002** | -1.92E-04 | 0.002** |
| Time-Since-Rainfall * Nearest Stream Outlet | - | - | -1.85E-04 | 0.074* |

* Predictor significant at $p < 0.1$
** Predictor significant at $p < 0.05$

Analysis of fecal coliform exceedance was limited by the low number of exceedance cases relative to total samples collected and a lack of knowledge of coastal hydrodynamics for inclusion in upcurrent/upstream source proximity measurements. Conclusions should not be drawn from results of one analysis method alone. Consideration of the chi-square test of independence and logistic regression results in tandem reduces uncertainty associated with statistical interpretation and sheds light on drivers of fecal coliform contamination. Results of these analyses point to time-since-rainfall and marina distance as the most informative predictors of fecal coliform exceedance. The relationship between rainfall and fecal coliform contamination identified in this analysis highlights the importance of nonpoint source contributions to coastal pathogen pollution. Similarly, the connection between marine vessel wastewater discharges and coastal pathogen contamination can be inferred from the estimated relationship between marina distance and fecal coliform exceedance.

Exceedance analysis results do not present a clear link between coastal pathogen contamination and fecal coliform point source discharges or stream/gut outlets. The insensitivity of fecal coliform exceedance to stream outlet distance is partially at odds with the proposed relationship between rainfall and exceedance, since pathogens which may be present in stormwater enter coastal waters at stream outlet points. Near-stream samples taken during dry periods which were included in analysis may cloud the relationship between exceedance and stream outlet distance. The introduction of a term representing the interaction between time-since-rainfall and stream outlet distance in logistic regression modeling suggests that this may be the case. Interaction terms are commonly included in regression modeling and allow for investigation of the combined effect of multiple predictor variables. Here, the product of time-since-rainfall and stream outlet distance was calculated for each sample, with near-zero values associated with samples collected near a stream outlet at times when storm runoff is encouraged by recent rainfall. Wald test results with the inclusion of the interaction term in logistic regression (Table 2-22) indicate that the time-since-rainfall ($p = 0.527$) and stream outlet distance ($p = 0.898$) terms alone are much less likely to be predictors of exceedance relative to their interaction term ($p = 0.074$).

## 2.6 Recommended Locations for Targeted Pathogen Monitoring

An effective water quality monitoring strategy is one which addresses its objectives despite analytical and financial constraints. A monitoring strategy specifically designed to identify USVI pathogen sources could aid watershed planning and source regulation efforts. In order to inform the planning of targeted pathogen monitoring, coastal locations that may be at risk for pathogen contamination were identified. At-risk locations were determined through application of the logistic regression model of fecal coliform exceedance to USVI coastal areas (areas within 500 meters of the coastline). Stepwise regression was used to identify the regression model that best fit observed exceedance data, and provided a model with time-since-rainfall and nearest marina distance as exceedance predictors. A GIS grid of marina distance was generated for coastal areas at 30-meter resolution. Grid cell values were quantified as the straight-line distance (in meters) from the grid cell center to the nearest marina. For each grid cell location, the fecal coliform exceedance logistic regression model was applied to estimate the logit of fecal coliform exceedance. Fecal coliform exceedance probability at each coastal grid cell location was then calculated from modeled logit values.

Estimated fecal coliform exceedance probability is illustrated in Figure 2-21 (St. Croix), Figure 2-22 (St. John), and Figure 2-23 (St. Thomas) for the case where samples are collected on the same day as a rainfall event (time-since-rainfall term in logistic regression model set to 0 days). Maps of estimated exceedance probability for alternative values of the time-since-rainfall term are not provided, as relative differences between coastal locations are not affected with varied time-since-rainfall values.

Exceedance probability maps provide an indication of pathogen contamination susceptibility; however, targeted monitoring of coastal waters should not be based on exceedance probability maps alone. A thorough monitoring strategy should include sampling of susceptible areas and areas with varied local and upstream conditions to isolate pathogen sources and to better quantify their relative contribution to pathogen contamination.

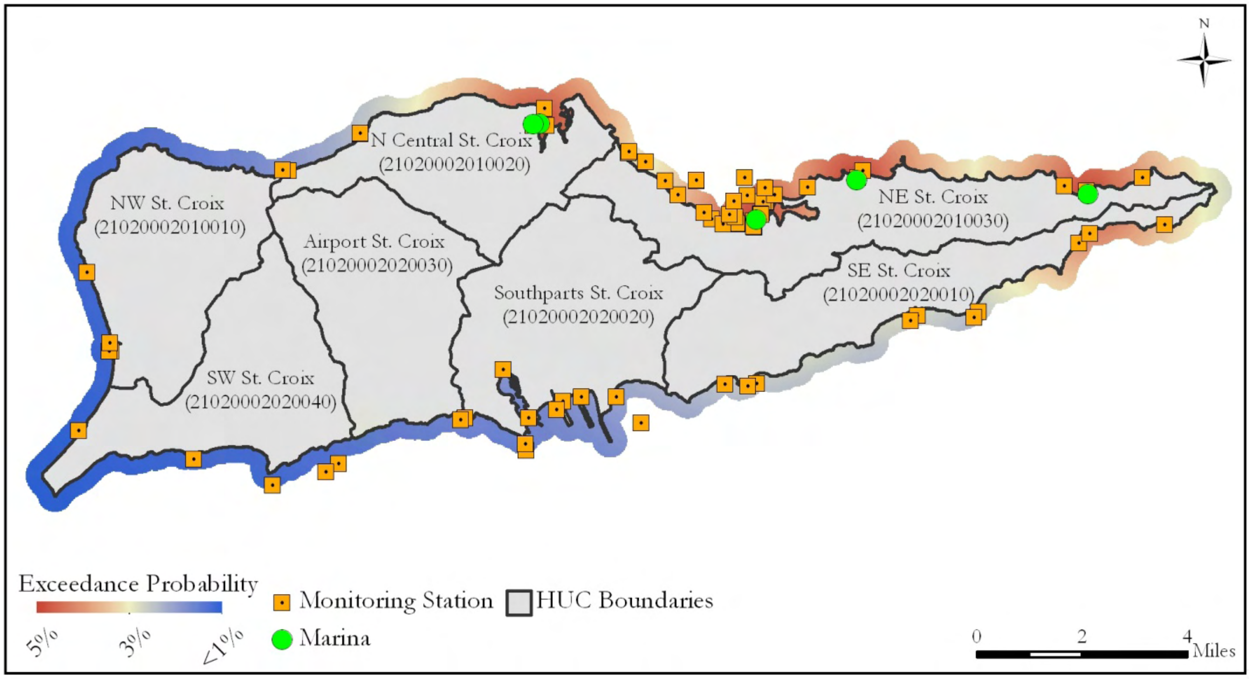



**Figure 2-21 Estimated fecal coliform exceedance probability within St. Croix coastal waters (for time elapsed since rainfall = 0 days).**

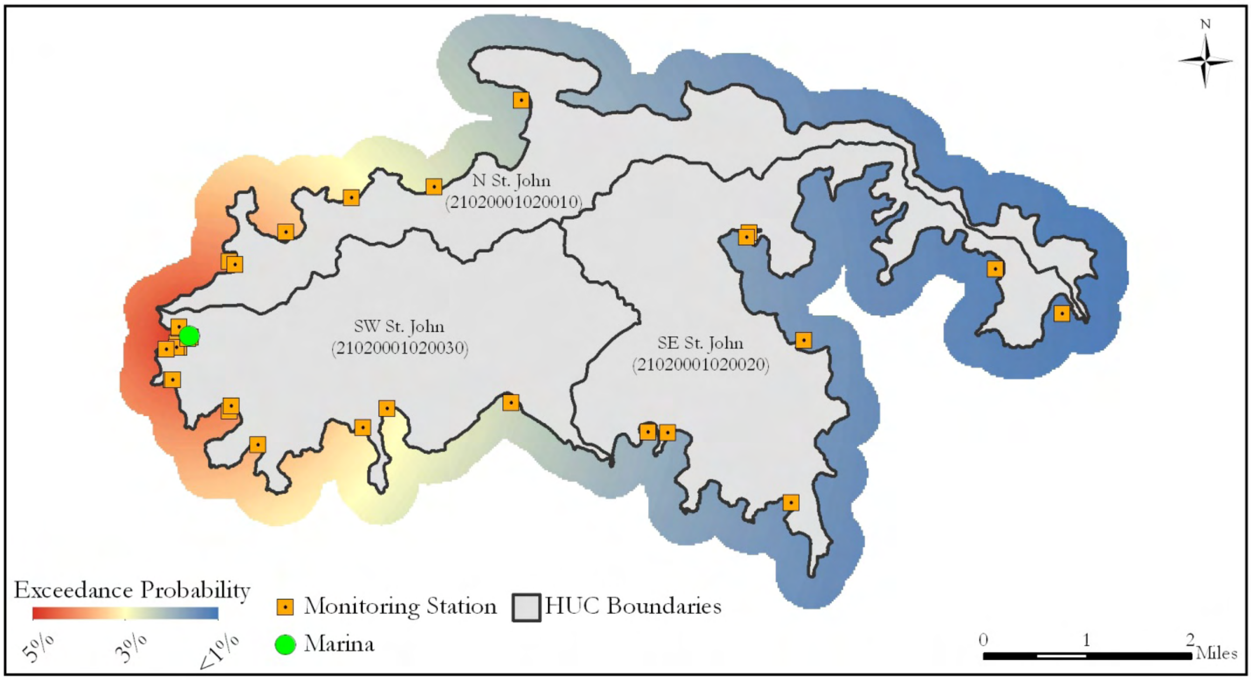



**Figure 2-22 Estimated fecal coliform exceedance probability within St. John coastal waters (for time elapsed since rainfall = 0 days).**

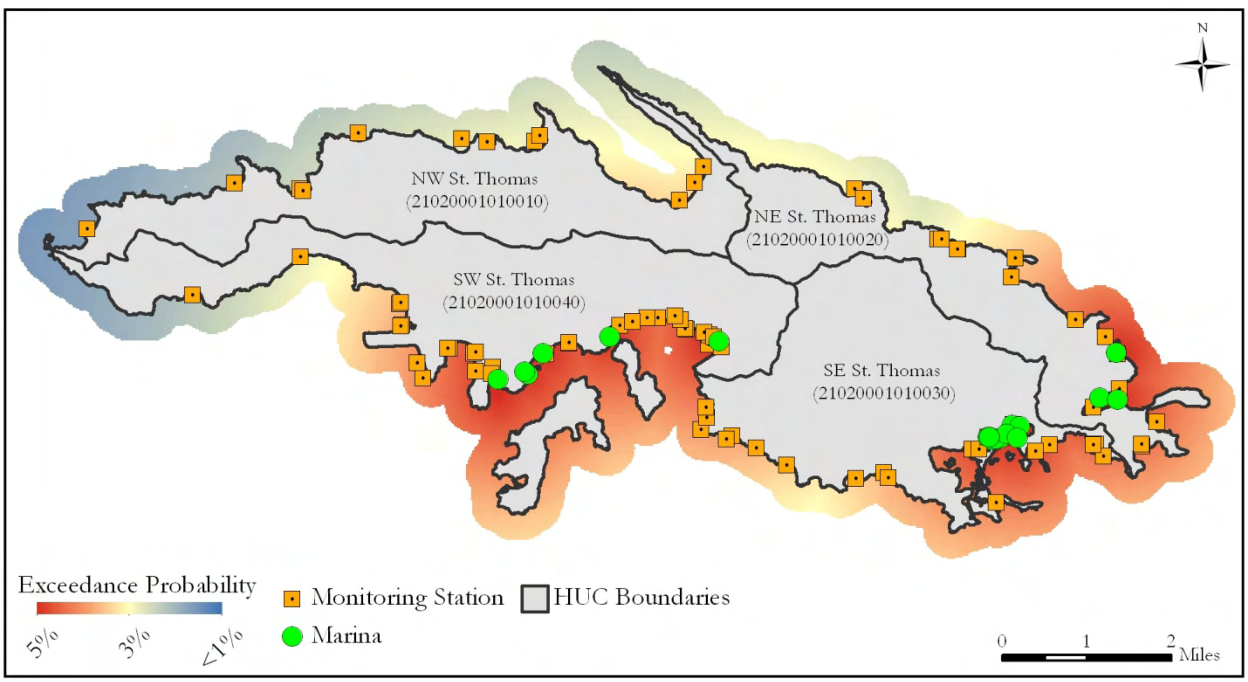



**Figure 2-23 Estimated fecal coliform exceedance probability within St. Thomas coastal waters (for time elapsed since rainfall = 0 days).**

## 2.7 Conclusions

Tourism in the USVI accounts for 42% of GDP, and the industry depends largely on the biological and recreational opportunities provided by the coastal waters and associated coral reefs (World Resources Institute, 2002). Increases in runoff from the USVI have the potential to impact these resources with elevated pollutant loads. In particular, fecal coliform pollution is suspected to cause coral reef diseases (Kaczmarsky, Draud, & Williams, 2005) and is a known cause of illness in humans who recreate in waters impacted by fecal coliform. Results of water quality trend analysis for the USVI indicate that fecal coliform levels in coastal waters have increased on the islands of St. Thomas and St. Croix from 2000 to 2008. The results are statistically significant and point to marinas and nonpoint sources as the most likely contributors of these pathogens. Land use changes on the islands during this same time period are estimated to have contributed to increased fecal coliform loading on St. Thomas and St. John and a decrease in fecal coliform loading on St. Croix. Land use changes and the resulting changes in runoff alone are therefore not likely sufficient to cause the increasing levels of fecal coliform observed. As indicated in Chapter 1, however, failing OSDS (which were not included in the L-THIA modeling) are likely to be significant nonpoint sources of fecal coliform. Addressing these failing systems, along with improved management of marinas, should therefore be prioritized to reverse the increasing trend seen in coastal fecal coliform levels. Additionally, protection of undeveloped areas on the islands (particularly on St. John and St. Thomas) should continue to be pursued as a strategy for minimizing increases in runoff and nonpoint sources of pollution.

Additional monitoring of coastal waters is important to effective watershed planning on the USVI. It is recommended that future monitoring be conducted in the areas indicated as having a high fecal coliform exceedance probability in Figure 2-21, Figure 2-22, and Figure 2-23. However, it is also important that sampling continue in areas outside of these zones and on varying numbers of days since rainfall. This will help to ensure a “balanced” dataset for continued refinement of the logistic regression model that predicts sources and locations of fecal coliform exceedance. Storm event monitoring of USVI guts/streams should also be a part of future sampling efforts. Results of this sampling would provide valuable data for calibration of rainfall-runoff models such as L-THIA (data that are currently lacking).

# 3 Green Infrastructure

## 3.1 Introduction

A common element of efforts to improve or maintain water quality is the management of runoff from developed lands (stormwater). Throughout the US, recent stormwater management planning has increasingly incorporated green infrastructure technologies. The green infrastructure approach uses Best Management Practices (BMPs) and Low Impact Development (LID) techniques that use natural, on-site features to reduce stormwater volume and prevent a direct connection between untreated or inadequately treated stormwater and receiving waters.

A valuable step in green infrastructure planning is the application of process-based hydrological models to simulate the natural and artificial hydrology of a region and estimate stormwater volumes and pollutant loads. Additionally, stormwater planning tools are available that use model output to estimate stormwater and pollutant attenuation by green infrastructure practices. This section presents results of stormwater modeling analysis performed for USVI watersheds using EPA's System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) model, discusses the potential for SUSTAIN to be applied as a stormwater planning tool in the USVI, and provides recommendations for stormwater management initiatives based on a review of existing stormwater management resources.

## 3.2 Watershed Modeling Analysis

Watershed hydrology was simulated in SUSTAIN for 50 USVI subwatersheds delineated by the USVI DPNR and described in the *2010 USVI Integrated Water Quality Monitoring & Assessment Report* (Virgin Islands Department of Planning and Natural Resources, 2010) (Figure 3-1 through Figure 3-3). Subwatersheds vary widely in size (100 – 8,000 acres), land use (0 – 34% impervious cover), and topography (average slope ranging from 2 – 56%) (Table 3-1). Subwatersheds generally contain multiple drainage channels (guts) that discharge to coastal waters. Dominant natural cover types include deciduous forest and shrubland. Agriculture is limited in extent within subwatersheds, with the largest area devoted to pasture (maximum of 26% of subwatershed area) rather than cultivated crops (maximum of 4% of subwatershed area). Residential areas consist of high-density development (generally near the coastline) and moderate to low-density development in mixed land use areas. Roadways include paved and unpaved portions (both classified as impervious in model simulations), which run from the coast to upland areas and traverse steep slopes.

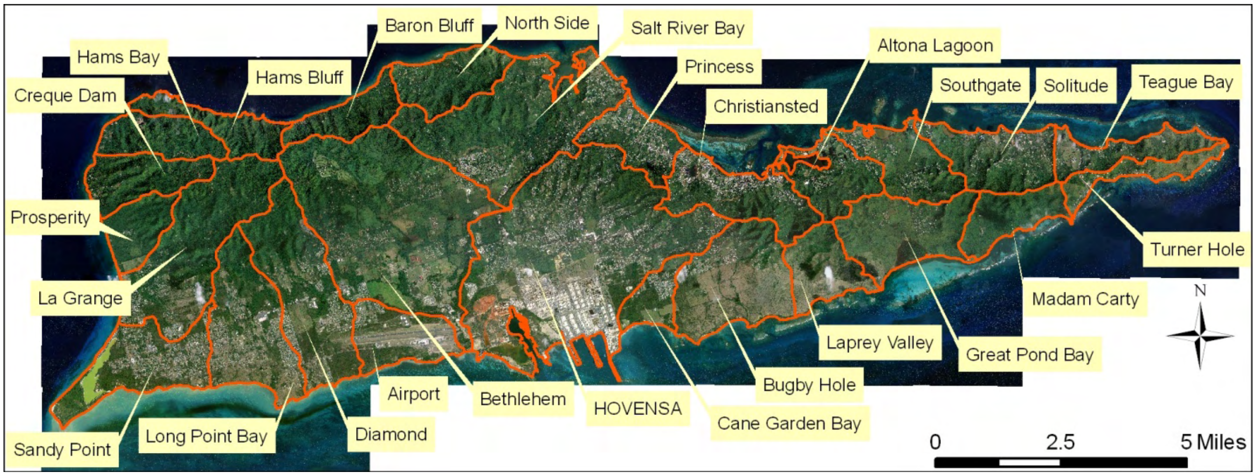



**Figure 3-1. St. Croix subwatersheds.**

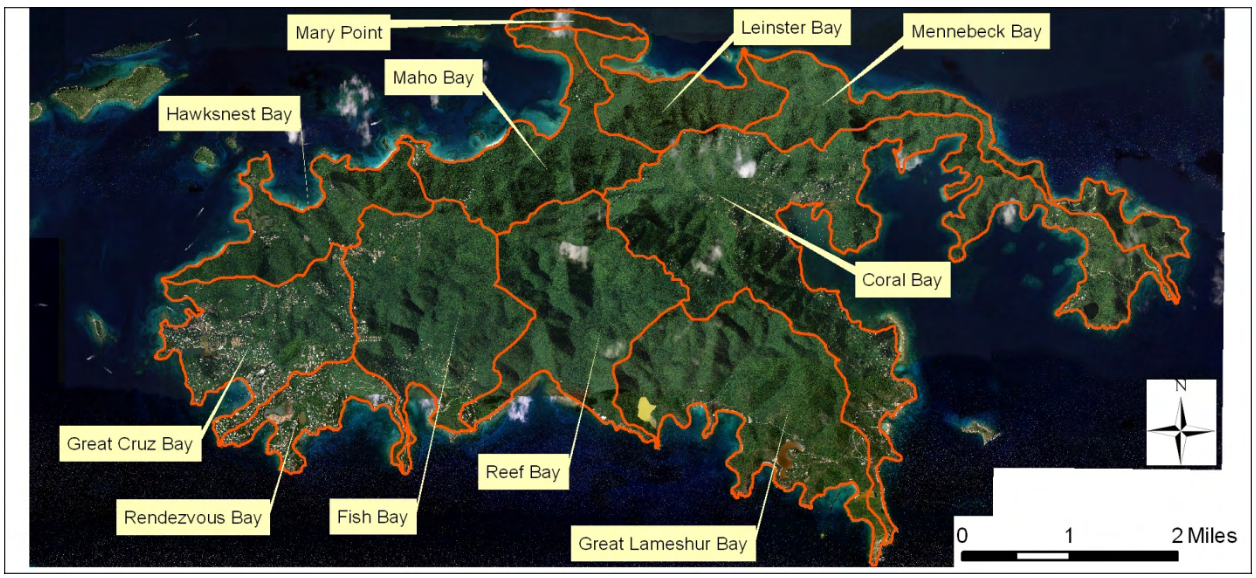



**Figure 3-2. St. John subwatersheds.**

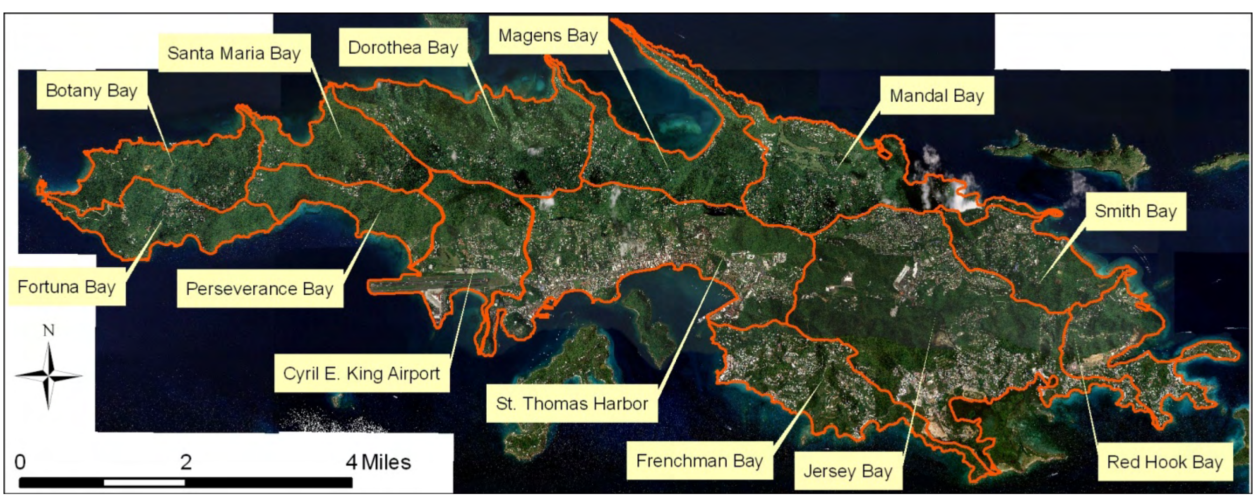



**Figure 3-3. St. Thomas subwatersheds.**

**Table 3-1. Subwatershed characteristics by 14-digit HUC.**

| HUC | Subwatershed | Area (acres) | Impervious Surface[1] | Watershed Slope |
|---|---|---|---|---|
| NW St. Thomas (21020001010010) | Magens Bay | 1104 | 10% | 34% |
| | Dorothea Bay | 1682 | 11% | 32% |
| | Santa Maria Bay | 789 | 7% | 32% |
| | Botany Bay | 879 | 6% | 31% |
| NE St. Thomas (21020001010020) | Red Hook Bay | 858 | 24% | 20% |
| | Smith Bay | 862 | 21% | 22% |
| | Mandal Bay | 1592 | 16% | 34% |
| SE St. Thomas (21020001010030) | Frenchman Bay | 1180 | 20% | 30% |
| | Jersey Bay | 3485 | 21% | 23% |
| SW St. Thomas (21020001010040) | Fortuna Bay | 801 | 8% | 34% |
| | Perseverance Bay | 710 | 5% | 39% |
| | Cyril E. King Airport | 1126 | 30% | 25% |
| | St. Thomas Harbor | 2497 | 34% | 28% |
| N St. John (21020001020010) | Mary Point | 110 | 0% | 56% |
| | Leinster Bay | 612 | 1% | 38% |
| | Mennebeck Bay | 813 | 1% | 36% |
| | Hawksnest Bay | 777 | 5% | 35% |
| | Maho Bay | 984 | 4% | 40% |
| SE St. John (21020001020020) | Coral Bay | 3006 | 8% | 37% |
| | Great Lameshur Bay | 1679 | 2% | 37% |
| SW St. John (21020001020030) | Reef Bay | 1395 | 1% | 42% |
| | Fish Bay | 1487 | 6% | 32% |
| | Great Cruz Bay | 1037 | 20% | 28% |
| | Rendezvous Bay | 420 | 17% | 31% |
| NW St. Croix (21020002010010) | Hams Bluff | 979 | 1% | 42% |
| | Creque Dam | 1207 | 4% | 26% |
| | Prosperity | 888 | 2% | 17% |
| | La Grange | 3257 | 8% | 21% |
| | Hams Bay | 1104 | 3% | 31% |
| N Central St. Croix (21020002010020) | Salt River Bay | 4157 | 11% | 19% |
| | North Side | 1278 | 6% | 29% |
| | Baron Bluff | 929 | 5% | 36% |
| NE St. Croix (21020002010030) | Teague Bay | 1021 | 9% | 25% |
| | Solitude | 1641 | 10% | 22% |
| | Southgate | 1398 | 10% | 15% |
| | Altona Lagoon | 1241 | 11% | 19% |
| | Christiansted | 1793 | 22% | 22% |
| | Princess | 1102 | 21% | 13% |
| SE St. Croix (21020002020010) | Turner Hole | 714 | 10% | 30% |
| | Madam Carty | 1043 | 1% | 24% |
| | Great Pond Bay | 2000 | 4% | 15% |
| | Laprey Valley | 1135 | 1% | 20% |
| | Bugby Hole | 2502 | 4% | 11% |
| Southparts St. Croix (21020002020020) | HOVENSA | 8135 | 29% | 8% |
| | Cane Garden Bay | 677 | 10% | 7% |
| Airport St. Croix (21020002020030) | Airport | 1291 | 18% | 4% |
| | Bethlehem | 6563 | 9% | 12% |
| SW St. Croix (21020002020040) | Sandy Point | 2017 | 15% | 2% |
| | Long Point Bay | 2482 | 13% | 10% |
| | Diamond | 2921 | 10% | 13% |

[1] From 2007 NOAA C-CAP Land Cover Dataset.

Existing runoff data collected in USVI guts provides insight into USVI hydrology. Large volumes of runoff are produced during and immediately after large rainfall events. Observed runoff response to small to moderate storms varies and is likely dependent on antecedent moisture conditions (soil moisture at the start of rainfall). Delayed runoff contributions from groundwater sources (baseflow) vary by location, season, and year, creating ephemeral to intermittent flow conditions (Figure 3-4).

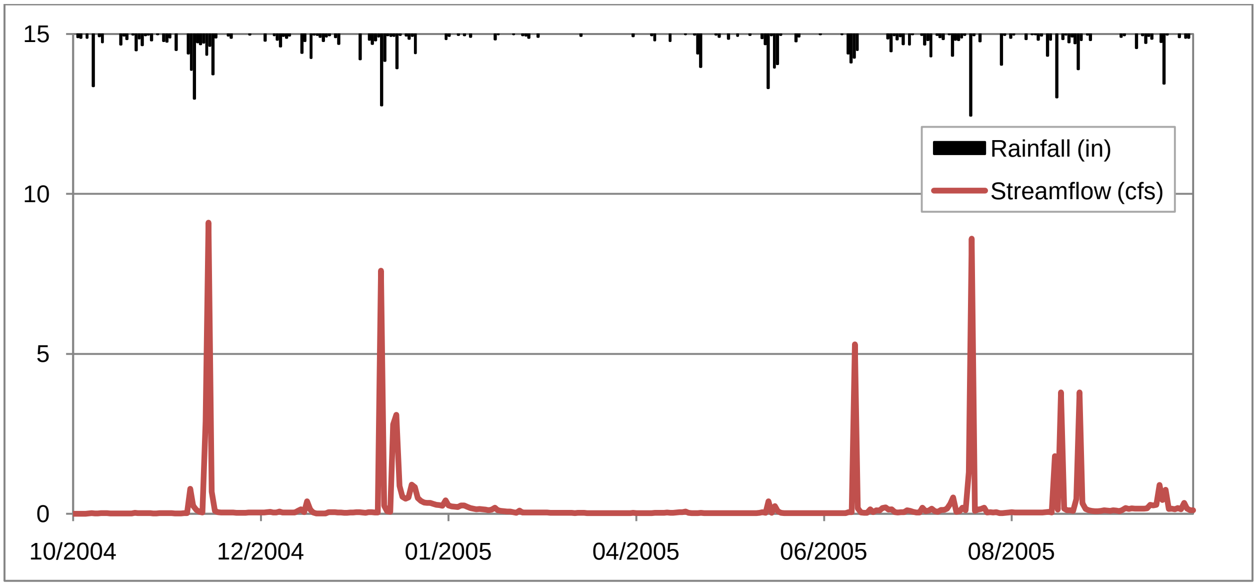



**Figure 3-4. Daily streamflow data from Bonne Resolution Gut (USGS ID 50252000) and daily rainfall observations from the Wintberg, St. Thomas (NCDC ID 679450) weather station for water year 2005. The short duration of high flow and baseflow conditions are typical of USVI guts.**

SUSTAIN simulations were configured to estimate runoff and pollutant loading from USVI subwatersheds over the period 10/01/1999 through 09/30/2009 (water years 2000 – 2009). Modeled pollutants included total suspended solids (TSS) and fecal coliform bacteria. These pollutants were selected for analysis due to widespread issues of sedimentation and contamination by pathogenic bacteria in USVI coastal waters (Virgin Islands Department of Planning and Natural Resources, 2010).

The physical, process-based nature of SUSTAIN algorithms allows for an investigation of runoff generation mechanisms within modeled watersheds. Calibration simulations for gaged watersheds indicate that, in upland vegetated areas, widespread surface runoff resulting from infiltration-excess overland flow is minimal. Instead, highly permeable surface soils allow for infiltration of most rainfall, and dominant natural runoff generation processes are likely localized saturation overland flow and rapid subsurface outflow (see 3.5Appendix A for a complete review of SUSTAIN modeling). These findings are in line with runoff generation mechanisms discussed in hydrological studies of St. John hillslopes and headwater watersheds (Macdonald, Sampson, & Anderson, 2001; Ramos-Scharron & MacDonald, 2007).

Runoff estimates for USVI subwatersheds are provided in Table 3-2. Estimates reflect maximum potential storm runoff (total runoff minus baseflow) to coastal waters. Observed streamflow data from coastal areas were not available to inform an assessment of the proportion of impervious runoff entering coastal waters (versus that routed to pervious areas), and all impervious runoff was assumed to have a direct connection to coastal waters. As a reference for evaluating stormwater volume within subwatersheds, SUSTAIN simulations were configured for a "pre-development" scenario, where the developed land area (impervious, open developed, agriculture) was represented as the dominant natural cover type. A comparison of runoff estimates from pre- and post-development simulations is provided in Figure 3-5. Note that pre-development runoff estimates are similar for subwatersheds on the same island (or equal if the same climatological input data were used) due to the use of a single set of calibrated values for select parameters for each island. Differences between pre- and post-development runoff values are a reflection of impervious surface cover and provide an estimate of stormwater quantity in USVI subwatersheds. Subwatersheds with large stormwater estimates can be further evaluated to identify the presence of existing drainage infrastructure and the potential for green infrastructure projects.

**Table 3-2. Average runoff and pollutant yields for USVI subwatersheds over the period of analysis (water years 2000 – 2009). Reported runoff estimates are storm runoff (total runoff minus baseflow).**

| HUC | Subwatershed | Runoff (in/yr) | TSS Yield (lbs/acre/yr) | Fecal Coliform Yield (billion/ac/yr) |
|---|---|---|---|---|
| NW St. Thomas (21020001010010) | Botany Bay | 4.7 | 93 | 65.6 |
| | Santa Maria Bay | 6.1 | 122 | 84.7 |
| | Dorothea Bay | 5.6 | 97 | 63.6 |
| | Magens Bay | 5.6 | 95 | 61.6 |
| NE St. Thomas (21020001010020) | Mandal Bay | 6.4 | 100 | 63.0 |
| | Smith Bay | 10.9 | 207 | 130.1 |
| | Redhook Bay | 11.4 | 214 | 134.7 |
| SE St. Thomas (21020001010030) | Frenchman Bay | 15.1 | 307 | 198.6 |
| | Jersey Bay | 7.5 | 116 | 72.3 |
| SW St. Thomas (21020001010040) | Fortuna Bay | 5.3 | 99 | 66.3 |
| | Perseverance Bay | 12.1 | 297 | 215.7 |
| | Cyril E. King Airport | 20.3 | 468 | 313.3 |
| | St. Thomas Harbor | 10.4 | 168 | 107.1 |
| N St. John (21020001020010) | Hawksnest Bay | 8.3 | 135 | 94.3 |
| | Maho Bay | 8.0 | 132 | 92.8 |
| | Mary Point | 13.2 | 239 | 175.9 |
| | Leinster Bay | 7.7 | 137 | 99.9 |
| | Mennebeck Bay | 8.0 | 142 | 103.5 |
| SE St. John (21020001020020) | Coral Bay | 8.8 | 135 | 90.9 |
| | Great Lameshur Bay | 7.8 | 137 | 99.6 |
| SW St. John (21020001020030) | Great Cruz Bay | 12.6 | 183 | 114.6 |
| | Fish Bay | 8.5 | 136 | 93.4 |
| | Reef Bay | 8.8 | 156 | 114.2 |
| | Rendezvous Bay | 10.5 | 147 | 92.6 |
| NW St. Croix (21020002010010) | Hams Bluff | 3.3 | 84 | 64.1 |
| | Hams Bay | 3.6 | 80 | 58.6 |
| | Creque Dam | 3.7 | 81 | 58.5 |
| | Prosperity | 3.4 | 81 | 61.0 |
| | La Grange | 4.3 | 84 | 58.4 |
| N Central St. Croix (21020002010020) | Baron Bluff | 3.9 | 79 | 56.0 |
| | North Side | 7.2 | 162 | 116.5 |
| | Salt River Bay | 5.0 | 96 | 66.3 |
| NE St. Croix (21020002010030) | Princess | 8.4 | 236 | 101.6 |
| | Christiansted | 9.4 | 246 | 101.0 |
| | Altoona Lagoon | 8.0 | 236 | 93.3 |
| | Southgate | 6.2 | 189 | 76.6 |
| | Solitude | 7.3 | 216 | 85.4 |
| | Teague Bay | 9.7 | 313 | 123.6 |
| SE St. Croix (21020002020010) | Bugby Hole | 5.3 | 183 | 73.8 |
| | Laprey Valley | 5.0 | 185 | 74.0 |
| | Great Pond Bay | 5.1 | 177 | 71.1 |
| | Madam Carty | 5.1 | 184 | 72.7 |
| | Turner Hole | 6.5 | 178 | 68.3 |
| Southparts St. Croix (21020002020020) | HOVENSA | 8.1 | 203 | 89.8 |
| | Can Garden Bay | 4.6 | 133 | 54.5 |
| Airport St. Croix (21020002020030) | Bethlehem | 4.4 | 132 | 54.5 |
| | Airport | 6.3 | 177 | 77.4 |
| SW St. Croix (21020002020040) | Diamond | 4.6 | 125 | 49.9 |
| | Long Point Bay | 6.4 | 190 | 78.3 |
| | Sandy Point | 7.0 | 204 | 85.3 |

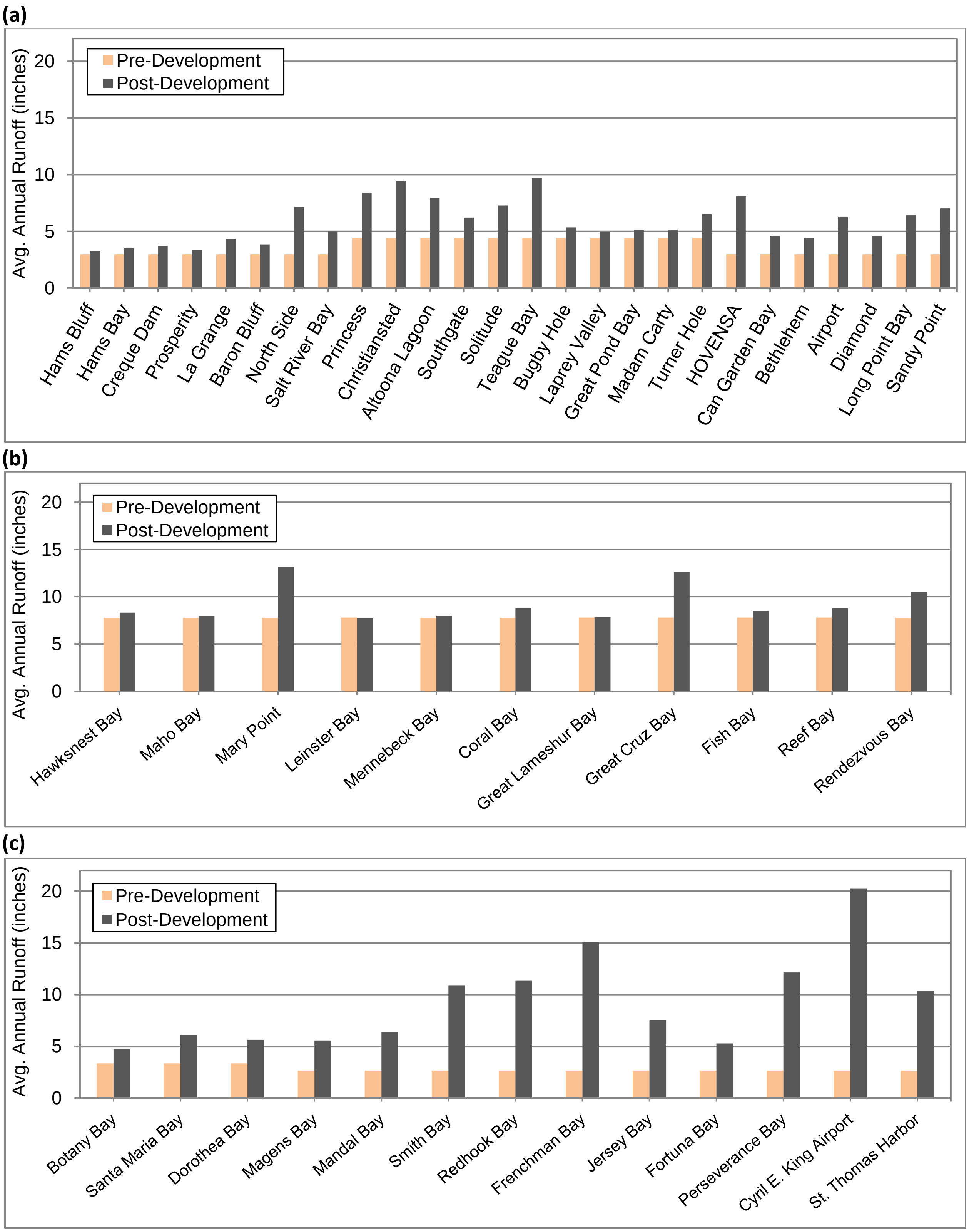
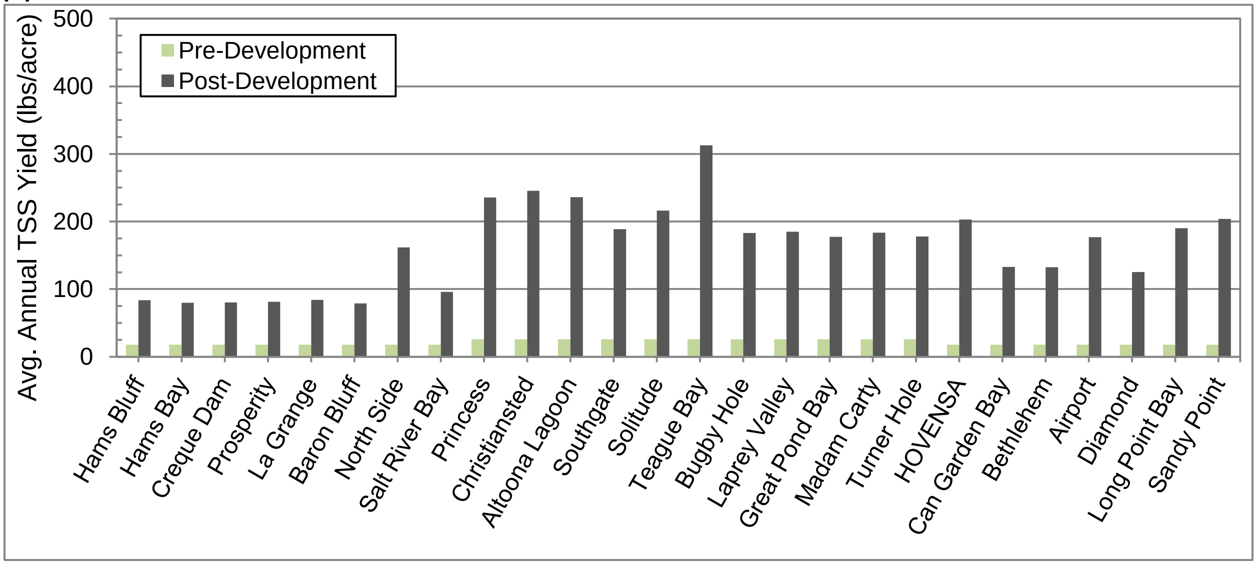


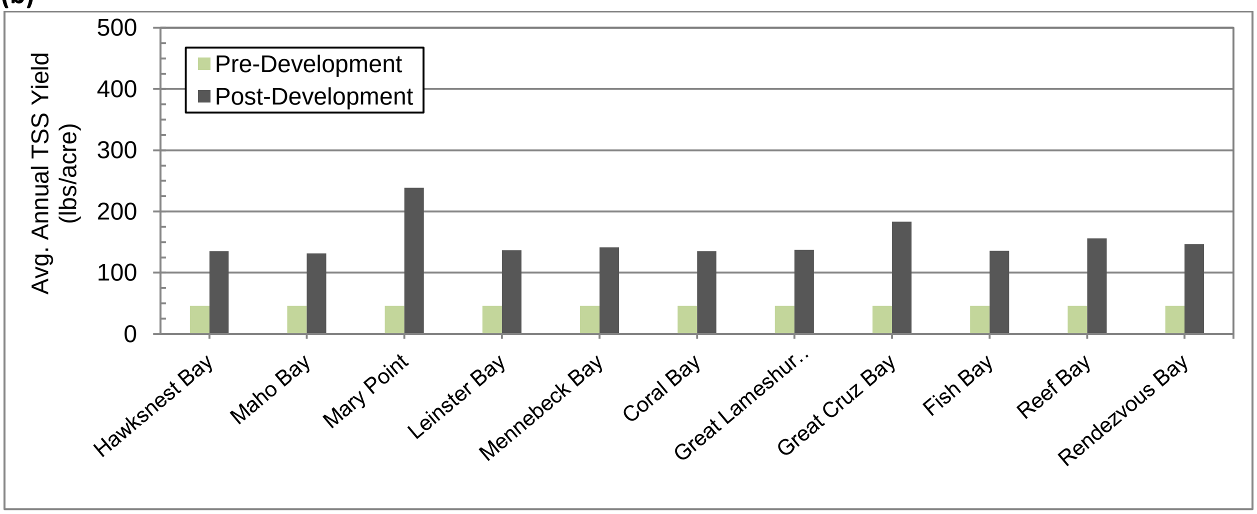

**Figure 3-5. Average annual storm runoff (total runoff minus baseflow) over the period of analysis (2000-2009) for St. Croix (a), St. John (b), and St. Thomas (c) subwatersheds for pre- and post-development modeling scenarios.**

SUSTAIN's land simulation algorithms were used to estimate TSS and fecal coliform loads over the period of analysis (Table 3-2). A comparison of pre- and post-development pollutant loads is presented in Figure 3-6 (for TSS) and Figure 3-7 (for fecal coliform). Like runoff estimates, differences between pre- and post-development loads are a reflection of impervious area in each subwatershed, and provide an estimate of the potential water quality benefits of stormwater BMP/LID implementation. A lack of inland water quality data, coupled with the large scale of modeling activities, prevented explicit representation of individual pollutant sources in SUSTAIN simulations. Instead, typical TSS and fecal coliform concentrations in runoff of modeled land uses were applied as model parameters. These values integrate the contributions of multiple potential nonpoint sources of TSS (unpaved roads, construction sites, etc.) and fecal coliform (animal waste, agricultural operations, etc.). Pollutant sources that are not associated with surface runoff in developed areas, such as failing septic systems (see Section 1. Sanitary Sewage), were not considered for estimation of stormwater loads, and results presented here should not be interpreted as total watershed loading estimates.

(a)




(b)




(c)

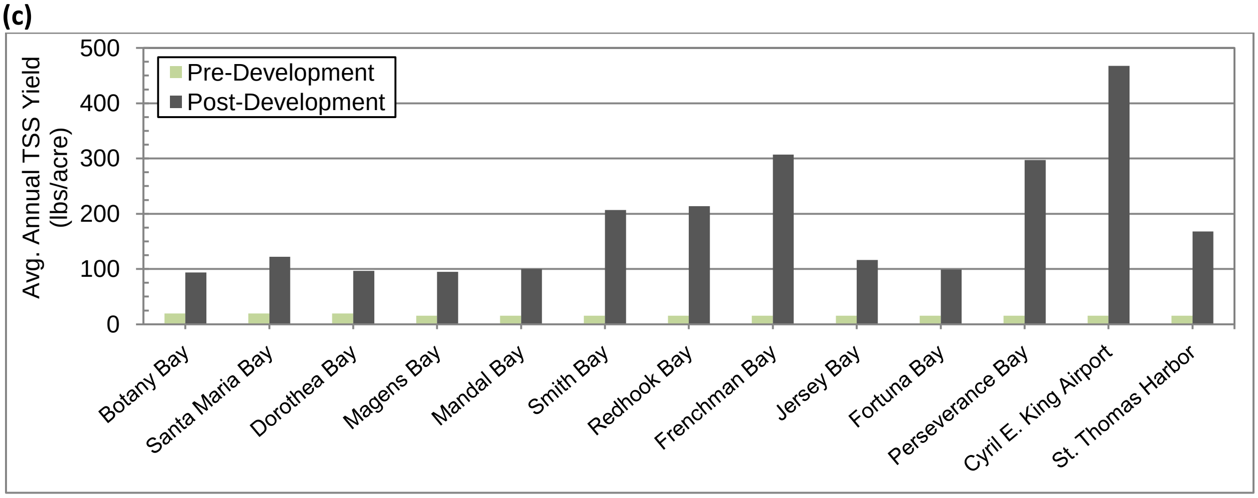



**Figure 3-6. Average annual TSS yield over the period of analysis (2000-2009) for St. Croix (a), St. John (b), and St. Thomas (c) subwatersheds for pre- and post-development modeling scenarios.**

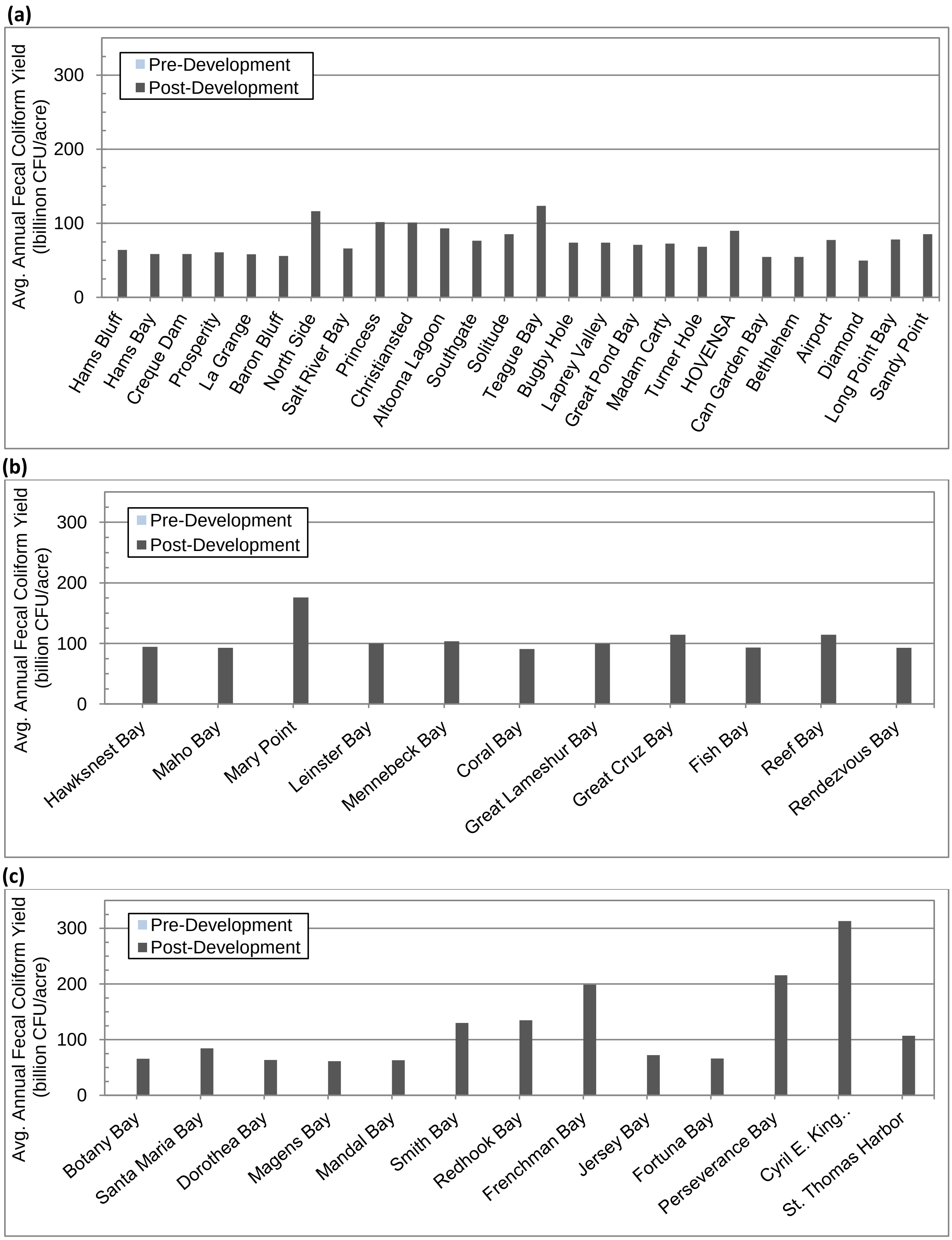



**Figure 3-7. Average annual fecal coliform yield over the period of analysis (2000-2009) for St. Croix (a), St. John (b), and St. Thomas (c) subwatersheds for pre- and post-development modeling scenarios.**

## 3.3 SUSTAIN as a Stormwater Planning Tool

A key resource for stormwater management planning by government agencies and island organizations is the *Virgin Islands Environmental Protection Handbook* (EPH) (University of the Virgin Islands Cooperative Extension Service, 2002). The EPH provides a comprehensive description of stormwater and pollutant sources, a review of BMP/LID practices suitable for the USVI, and direction on where and how these practices should be implemented. Stormwater BMPs/LID included in the EPH are separated into 3 general categories based on their primary method of stormwater volume and pollutant attenuation (Table 3-3): 1) practices that filter stormwater as it travels across the land surface (filtration practices); 2) practices that retain stormwater on the land surface (retention practices); and 3) practices that allow for infiltration of stormwater into the subsurface (infiltration practices).

**Table 3-3. BMP/LID types recommended in the *Virgin Islands Environmental Protection Handbook* (EPH) and supported in SUSTAIN. Items marked with (*) are not explicitly represented in SUSTAIN v1.0 but may be supported in future releases.**

| BMP/LID Type | EPH | SUSTAIN |
|---|---|---|
| ***Filtration Practices*** | | |
| Buffer Zone | ✓ | * |
| Grassed Swale | ✓ | ✓ |
| Sand Filter | ✓ | * |
| Water Quality Inlet | ✓ | |
| ***Detention Practices*** | | |
| Extended Detention (Dry) Pond | ✓ | ✓ |
| Wet Pond | | ✓ |
| Constructed Wetland | ✓ | * |
| ***Infiltration Practices*** | | |
| Porous Paver | ✓ | ✓ |
| Infiltration Trench | ✓ | ✓ |
| Bio-Retention Basin | ✓ | ✓ |
| ***Interception Practices*** | | |
| Rain Barrel | | ✓ |
| Cistern | | ✓ |
| Green Roof | | ✓ |

Due to the complexity of stormwater planning and variety of management options, it is often desirable to apply planning tools that provide insight beyond the general guidelines in the EPH and related documents. Computer-based planning tools allow users to simulate the positive effects of BMP/LID installation on water quantity and quality. SUSTAIN is one such tool that is capable of simulating a number of BMPs/LID using process-based runoff and pollutant attenuation algorithms and user-supplied BMP design specifications. Additionally, SUSTAIN includes a BMP siting tool to identify suitable areas for BMP/LID placement within the modeled domain. Further, SUSTAIN allows users to enter cost information related to BMP/LID construction and maintenance, and provides the opportunity to evaluate cost-effective BMP/LID design and placement options.

In order to assess SUSTAIN's stormwater management simulation capabilities and demonstrate its potential for application to USVI watersheds, a SUSTAIN simulation was configured for a portion of the Coral Bay subwatershed, St. John. The Coral Bay subwatershed was the subject of a recent pilot project for watershed planning in the USVI (Center for Watershed Protection, 2008), and stormwater runoff has been identified as the major contributor to degraded water quality in Coral Bay. The 2008 Coral Bay Watershed Management Plan highlights the area in the vicinity of Centerline Road in the central portion of the subwatershed as a priority area for stormwater master planning. Aerial imagery was used in conjunction with land cover and topographic data to delineate an upper and lower drainage area along Centerline Road for the demonstration simulation (Figure 3-8). This area is characterized by steep slopes, low to moderate density residential development, unpaved roads and driveways, and severely eroded guts.

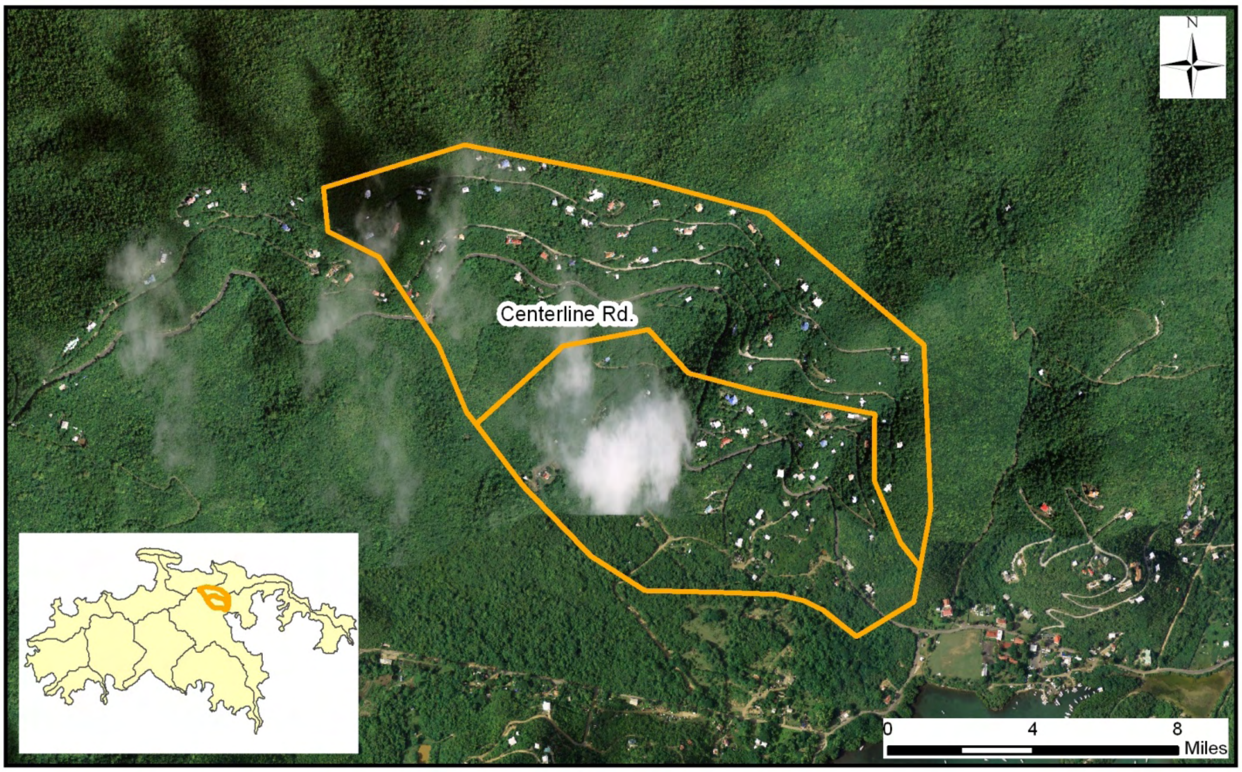



**Figure 3-8. Centerline Road drainage (upper & lower) in the Coral Bay subwatershed, St. John.**

Preparation of a stormwater management simulation in SUSTAIN consists of 3 main steps: 1) configure the stormwater management scenario in SUSTAIN's ArcGIS interface; 2) estimate runoff and pollutant loads input to BMP/LID features using SUSTAIN's internal land simulation option, or import externally-generated runoff and pollutant data; and 3) define assessment points for evaluating runoff and pollutant attenuation and cost optimization. SUSTAIN includes a BMP siting tool to aid in the design of the simulated management scenario. The BMP siting tool uses spatial data on site topography, land cover, soils, and groundwater conditions, and default BMP/LID suitability criteria derived from the EPA *Stormwater BMP Design Guide* (2004). Suitability maps were developed for the Centerline Road drainage for all BMP/LID types supported by SUSTAIN. A comparison of BMPs/LID supported by SUSTAIN and those included in the EPH is provided in Table 3-3. SUSTAIN supports most BMPs/LID recommended by the EPH, as well as additional site-scale green infrastructure practices (rain barrels, cisterns, green roofs).

BMP suitability maps for the Centerline Road drainage show limited suitability for BMP installation (mainly due to steep slopes). Select portions of the Centerline Road drainage were appropriate for bio-retention basins. A bio-retention basin (aka rain-garden) is a green infrastructure practice that uses a shallow, landscaped depression to allow for ponding and infiltration of stormwater generated from small (<2-5 acres) areas. Bio-retention basins have been promoted for use throughout the USVI, and were the subject of a stormwater management demonstration project in St. Croix sponsored by government agencies and local organizations (Virgin Islands Resource Conservation & Development Council, 2011) .

Two potential Centerline Road stormwater management scenarios were configured in SUSTAIN. One scenario included multiple (10) bio-retention basins in the upper and lower drainage areas. The second scenario included 10 bio-retention basins in the upper drainage area and a single dry detention pond in the lower drainage area. Bio-retention and dry pond design and cost parameters were based on EPH guidelines, SUSTAIN's default values, and information provided in the SUSTAIN manual. Runoff and pollutant loading was simulated using SUSTAIN's internal land simulation option and parameter values developed for the greater Coral Bay subwatershed. BMP simulation output includes pre- and post-BMP runoff and pollutant estimates, and cost information for each management scenario. Results of the Centerline Road simulations (Figure 3-9) show that the bio-retention scenario provides higher runoff and pollutant reduction relative to the bio-retention and dry pond scenario at a lower cost ($15,470 versus $170,689).

SUSTAIN allows users to designate certain BMP design specifications as decision variables that can vary between minimum and maximum values. These decision variables are used as part of SUSTAIN's cost optimization features. Optimization algorithms evaluate the ability of alternative management scenarios to meet user-specified runoff and pollutant management targets, as well as costs associated with each modeled scenario. Optimization can be configured to focus on minimizing costs or maximizing cost-effectiveness at a particular assessment point. For demonstration purposes, an optimization scenario was setup for the Centerline Road drainage with the number of bio-retention basins and presence/absence of a dry pond configured as decision variables. Runoff and pollutant load management targets were established as 25% reductions from pre-BMP values. Figure 3-9 illustrates SUSTAIN output for the optimized BMP scenario. BMP optimization indicated management targets could be met at a minimum cost through the installation 16 bio-retention basins and no dry pond in the Centerline Road drainage (total cost of $12,360). Note that while results favor the installation of bio-retention basins in the Centerline Road drainage, these data should not be used for planning purposes due to a lack of site-specific BMP design and cost information, and lack of runoff and water quality data for model validation.

(a)

(b)

(c)

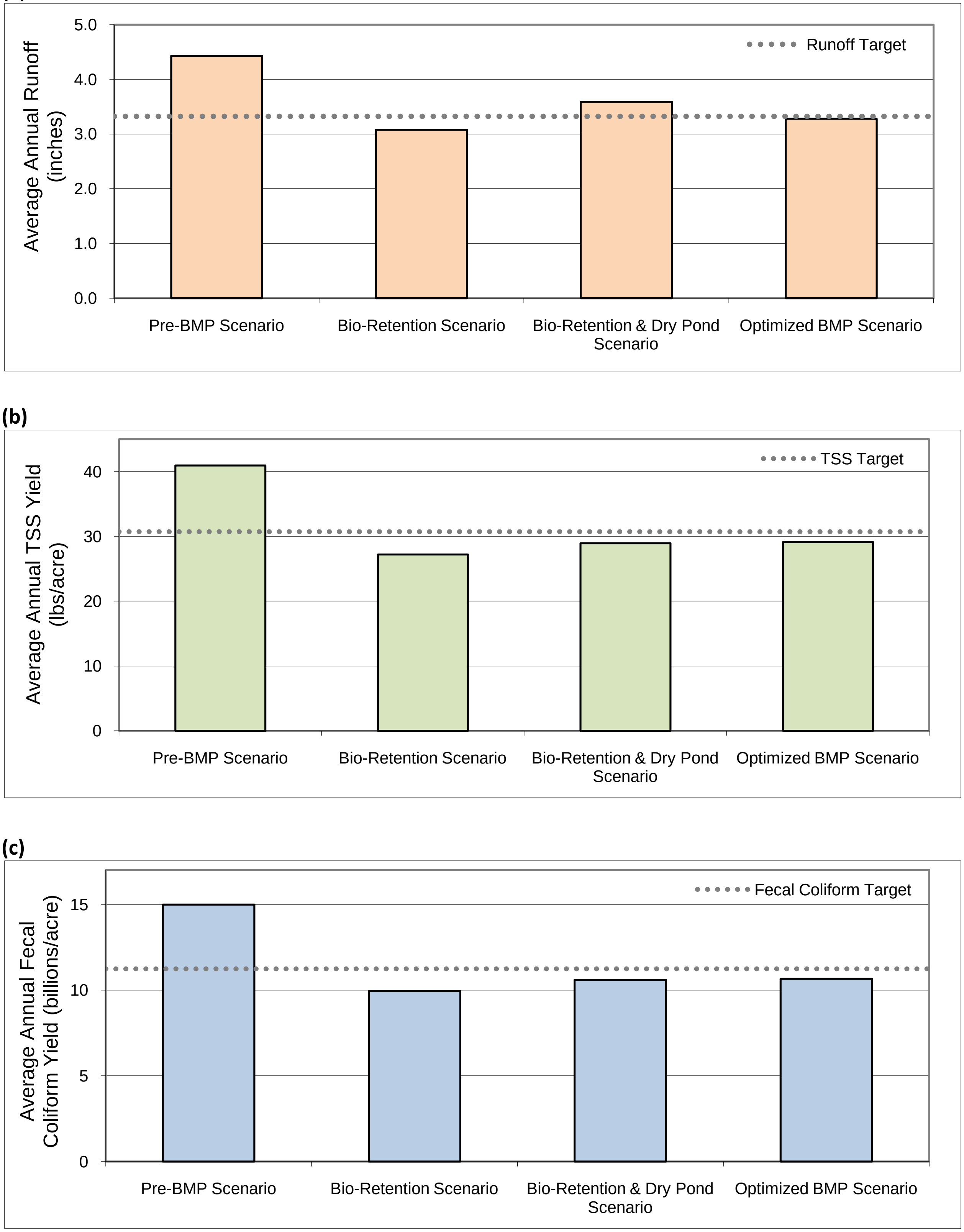



**Figure 3-9. Average annual runoff (a), TSS yield (b), and fecal coliform yield (c) for Centerline Road BMP simulation and optimization scenarios.**

SUSTAIN has the ability to serve as a single, integrated resource for simulation of watershed hydrology, simulation of stormwater management, and optimization of alternative stormwater management scenarios. Benefits of SUSTAIN include its use of established process-based methods for estimating runoff and pollutant loading, and attenuation by stormwater management practices. Additionally, SUSTAIN is able to simulate many BMP/LID types recommended in the EPH. However, several points must be considered before involving SUSTAIN or similar BMP simulation tools in future stormwater management planning. Such process-based models require detailed input and parameter data describing watershed conditions and characteristics of simulated stormwater controls. Large-scale stormwater management planning, therefore, requires a significant investment in resources to configure a detailed simulation and collect field data for model configuration and calibration. Though SUSTAIN includes an "aggregate BMP" method for simulating generalized BMP types for large watersheds, SUSTAIN's internal land simulation option for estimating runoff and pollutant inputs to BMPs is not compatible with the aggregate BMP method, and output from alternative watershed models must be used. Also, since SUSTAIN is a relatively new product in its initial release, documentation is minimal and the software is less user-friendly than well-established planning tools (such as EPA's Stormwater Management Model (SWMM) 5.0, whose BMP planning capacity is limited). Despite these points, SUSTAIN can serve as a powerful planning tool in the right context and with accompanying field investigations to verify parameter estimates and model output.

## 3.4 Recommendations for Stormwater Management Initiatives

To facilitate and streamline stormwater management initiatives by the territorial government, recommendations were developed from a review of the current USVI stormwater management framework, as well as a review of existing initiatives in other locations. The current framework for management of stormwater in the USVI includes contributions from federal and territorial agencies and non-governmental organizations (NGOs). Territorial regulations require permitting of point sources of stormwater discharge through the Territorial Pollutant Discharge Elimination System (TPDES). This process is coordinated by the USVI DPNR. Additionally, the USVI Department of Public Works (DPW) is involved with road design and drainage. The DPNR, US EPA, NOAA, and NRCS have undertaken recent watershed management efforts that have included stormwater planning components (Center for Watershed Protection, 2008; Horsley Witten Group, 2011). Efforts have included the Virgin Islands Resource and Development Council, the St. Croix Environmental Association, The Nature Conservancy, the University of the Virgin Islands Water Resources Research Institute, and others. These efforts represent coordinated attempts to identify stormwater management issues through field observations and stakeholder input, as well as sources of funding for potential stormwater management projects.

1) **Supplement TPDES stormwater regulations with stormwater quality and volume reduction standards.**

A number of states throughout the US have regulations in place that explicitly define water quality and quantity standards for stormwater discharge. Standards are generally applicable to stormwater discharged from new development or redevelopment following completion of construction activities. States such as Wisconsin, Vermont, and Virginia, for example, require an 80% reduction in stormwater TSS loads (relative to loads under no stormwater controls) for new development. Similarly, numerical standards have been developed for phosphorous loads (e.g., 40% reduction in total phosphorous for new development in Virginia). Standards for control of stormwater volume typically require maintenance of predevelopment discharge volumes (e.g., Vermont stormwater regulations state that post development 10 and 100 year storm peak discharges cannot exceed predevelopment discharges).

Additional approaches taken by states include varying stormwater quality and quantity standards according to location (Maryland has more stringent regulation for environmentally sensitive areas), the size of the developed area or impervious surface, and development type (new development versus redevelopment).

**2) Supplement TPDES stormwater regulations with green infrastructure mandates.**

TPDES regulations require stormwater controls to be specified as part of the permitting process for new development and redevelopment. While TPDES regulations encourage the use of BMPs, explicit control requirements are not outlined. Mandating the use of green infrastructure where appropriate could help to prevent water quality issues in areas undergoing rapid development while minimizing the need for traditional storm sewer and treatment systems. In August of 2007, EPA issued a memorandum that formally encouraged the use of green infrastructure for stormwater management under existing regulatory programs, and stormwater regulations at the state level have begun to incorporate green infrastructure requirements (U.S. Environmental Protection Agency, 2010). North Carolina requires impervious runoff from new development covering less than one acre to be managed through rain cisterns/barrels, rain gardens, or similar BMPs. States such as Maryland, California, West Virginia, and Ohio mandate the use of green infrastructure through stormwater infiltration/recharge requirements. Ordinances enacted at the county to city level, such as those described in the *Green Infrastructure Case Studies* report (U.S. Environmental Protection Agency, 2010), also include language that specifically requires green infrastructure, onsite stormwater management, and/or maintenance of natural hydrologic processes (infiltration, evaporation, etc.) following development. For example, Stafford County, VA, revised their stormwater management regulations in 2003 to require LID for new development. Stormwater regulations of Portland, OR, define a hierarchy for required controls to ensure that predeveloped hydrologic conditions are maintained through on-site management where practicable.

**3) Develop green infrastructure retrofit policies to address stormwater management in developed areas that currently lack stormwater controls.**

Large portions of developed areas in the USVI lack formal stormwater controls and are in need of stormwater retrofits. While the scope of TPDES regulations is adequate for new development, redevelopment, and existing development with designed drainage (Virgin Islands Department of Planning and Natural Resources, 2007), additional policies may be needed to facilitate stormwater management in developed areas with little/no management methods currently in place. Green infrastructure retrofits, in particular, could be a cost-effective method to reduce pollutant loading to guts and coastal waters. Additionally, the volume reduction benefits of green infrastructure retrofits could support gut restoration efforts in areas with severe channel erosion.

Regulatory and non-regulatory policy options are available to address green infrastructure retrofits. The *Managing Wet Weather with Green Infrastructure Municipal Handbook* (U.S. Environmental Protection Agency, 2008) provides a review of green infrastructure retrofit initiatives that have been undertaken by local governments. A number of these deal with the use of green infrastructure for stormwater management on public property. For example, the Green Alley Program of Chicago, IL, has resulted in the installation of porous pavement in 20 alleys per year since 2006. The City of Burnsville, MN, built roadside rain gardens to catch and treat road runoff, and solicited citizen participation in the project by garnering approval to build portions of the rain gardens on private property.

Green infrastructure retrofit initiatives designed for stormwater management on private lands generally involve incentives and/or reimbursements for property owners (U.S. Environmental Protection Agency, 2010). The Lake Michigan Rain Gardens Initiative of Milwaukee County, WI, offered discounted supplies to residents interested in planting their own rain garden. The City of Toronto enacted a Green Roofs Pilot Program that offers subsidies for green roof installation on homes and other buildings. Regulations requiring green infrastructure retrofits to private property are relatively rare, and have been most effective with compliance assistance programs. For example, Portland, OR, enacted an ordinance requiring disconnection of existing impervious cover from storm sewer systems in certain areas, and offered reimbursement for disconnection if completed prior to the established enforcement date.

**4) Consider the formation of a territorial stormwater utility or municipal stormwater utilities.**

A lack of coordination between agencies such as the DPNR and DPW, technical expertise in stormwater engineering, and agency presence in remote areas has hindered stormwater management in the USVI (Center for Watershed Protection, 2008). A dedicated stormwater utility comprised of individuals with extensive knowledge of current management practices could remedy these issues and streamline future management initiatives. There are several benefits to the formation of stormwater management utilities. Chief among them is the use of fees collected for stormwater management services to be applied to offset costs associated with stormwater retrofits, compliance assistance and incentive programs, and regulatory enforcement. Programs can be setup to allow fees to be reduced or waived if property owners or developers install green infrastructure. The *Managing Wet Weather with Green Infrastructure Municipal Handbook* (U.S. Environmental Protection Agency, 2008) includes a several examples of utility fee related green infrastructure incentives.

Options for stormwater utility establishment include the formation of a single territorial-wide stormwater utility (similar to the Virgin Islands Waste Management Authority and Virgin Islands Water and Power Authority) or municipal stormwater utilities. Should the local approach be preferred, actions can be taken by the territorial government to guide the establishment of municipal stormwater utilities. The State of Vermont has passed legislation that explicitly gives municipalities the authority to create stormwater utilities. Delaware's stormwater regulations encourage municipal stormwater utilities and include criteria for stormwater utility implementation, and the State of Maine has developed a model *s*tormwater utility ordinance to serve as a framework for communities interested in forming a stormwater utility.

**5) Continue stakeholder interaction and public outreach campaigns to improve understanding and awareness of stormwater issues, regulations, and programs.**

The Coral Bay, St. John, and East End, St. Croix watershed management projects (Center for Watershed Protection, 2008; Horsley Witten Group, 2011) are prime examples of positive interaction between government agencies and stakeholders that have the effect of improving natural resource health in the USVI. While these projects represent a key step toward improving citizen awareness of stormwater issues and regulations, each project has highlighted the need for additional outreach to USVI residents. Education and outreach programs are a common element of city and county stormwater management policies discussed in the *Green Infrastructure Case Studies* report (U.S. Environmental Protection Agency, 2010). Demonstration projects with descriptive signage, in particular, have been found to effectively provide residents with an understanding of the benefits of onsite stormwater controls, and allow residents to see their stormwater utility fees put to use. The St. Croix rain garden demonstration (Virgin Islands Resource Conservation & Development Council, 2011) is an example of a well-planned project that could be applied throughout the USVI. The City of Portland, OR, has organized walking and cycling tours to showcase demonstration sites that include a range of green infrastructure types. Additional outreach options include the design of how-to guides, press releases, and presentations to neighborhood associations or horticultural groups. The *Green Infrastructure Case Studies* report (U.S. Environmental Protection Agency, 2010) and *Managing Wet Weather with Green Infrastructure Municipal Handbook* (U.S. Environmental Protection Agency, 2008) each include additional tips for improving citizen awareness of stormwater management, as well as information on how these activities fit into larger stormwater management initiatives.

## 3.5 Conclusions

Improved stormwater management is needed throughout the USVI to address degraded water quality in coastal areas. The islands' complex topography, hydrology, and land use patterns present unique challenges to stormwater management planning. Watershed assessment and modeling tools can be used to ensure that attention and funding is directed where they are needed most, and where water quality benefits are likely to occur. Stormwater management planning in the USVI is further complicated by the lack of existing infrastructure, awareness of the problem, and well-defined policy. However, these issues allow for the development of stormwater policy and controls that emphasize cutting-edge, green infrastructure technologies where appropriate without the need to revise existing regulations or phase out aging infrastructure. Further, the site to neighborhood scale and highly-visible nature of green infrastructure practices are ideal for involving multiple stakeholders and increasing awareness of the importance of stormwater management for water quality improvements.

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# Appendix A SUSTAIN Model Setup, Calibration, and Validation

Simulation of watershed runoff and pollutant loading was conducted using EPA's System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) model. SUSTAIN combines established methods of stormwater modeling (through application of algorithms developed for EPA's Stormwater Management Model (SWMM) and Hydrologic Simulation Program FORTRAN (HSPF)) with a comprehensive set of stormwater management planning tools. The selection of SUSTAIN for modeling efforts was based on its ability to serve a single, integrated resource for simulation of watershed hydrology and optimization of stormwater and pollutant attenuation through Best Management Practice (BMP) and Low Impact Development (LID) implementation. Modeling objectives included: (1) develop a calibrated model of present-day storm hydrology for USVI watersheds; (2) simulate fecal coliform and total suspended solids (TSS) loading from USVI watersheds; (3) quantify potential stormwater and pollutant attenuation by BMPs/LID; and (4) demonstrate the potential for use of SUSTAIN to support future planning for the control and management of stormwater.

## A.1 Conceptual Model Design

SUSTAIN is a continuous, process-based hydrologic model. SUSTAIN algorithms account for runoff generation from 3 sources: (1) impervious area overland flow; (2) pervious area overland flow; and (3) saturated subsurface flow. SUSTAIN adopts a non-linear reservoir approach to model the land surface water balance, where accumulation of water on the land surface is a function of inflow (rainfall), outflow (evaporation; infiltration, calculated using the Green-Ampt model), and storage change. Accumulated surface water is converted to overland flow using the Manning equation. Subsurface dynamics are represented with a two-zone groundwater model. In this formulation, an upper unsaturated zone and lower saturated zone are defined with user-supplied storage, drainage, and evapotranspiration (ET) properties. Groundwater outflow is calculated as a function of water table elevation (U.S. Environmental Protection Agency, 2009).

SUSTAIN's surface and subsurface runoff simulation components were applied to model USVI hydrology in order to represent real-world conditions and processes. Approximately 10% of the USVI land area is covered by impervious surfaces, and the potential for impervious runoff exists within densely populated coastal areas, low-density upland areas, and along the island road network. Runoff generation processes in undeveloped areas are complex. Previous studies of USVI hydrology have identified minimal overland flow in vegetated upland regions, and point to rapid lateral subsurface flow and saturation overland flow in low-lying areas as primary runoff sources (Macdonald 1997; Ramos-Scherron & Macdonald 2007). Delayed groundwater outflow (baseflow) is highly variable by location and, where present, occurs during a short portion of the year, resulting in ephemeral to intermittent flow conditions in stream channels (U.S. Geological Survey, 1996).

SUSTAIN's water quality algorithms account for washoff of accumulated pollutants from the land surface during runoff events. The event mean concentration (EMC) method was applied to simulate TSS and fecal coliform loading from USVI watersheds. EMCs represent the ratio of total pollutant load to total runoff volume for a given runoff event, and have been the subject of numerous water quality studies, including the EPA's Nationwide Urban Runoff Program (U.S. Environmental Protection Agency, 1983) and its derivatives. SUSTAIN applies user-supplied EMC values to calculate pollutant loads based on internally generated runoff estimates.

## A.2 Model Configuration

SUSTAIN simulations were configured for USVI watersheds at the 14-digit HUC scale. Daily runoff, TSS concentration, and fecal coliform concentration were modeled using SUSTAIN's internal land simulation option. Continuous simulations were conducted for water years 2000 through 2009 (10/1/1999 - 9/30/2009) with a 1 month warm-up period (9/1/1999 – 9/30/1999). Model configuration consisted of specification of spatial data files in SUSTAIN's ArcGIS interface, definition of meteorological input data, and definition of parameters used for runoff and pollutant loading calculations.

Spatial input data included gridded land use data and subwatershed boundaries. Subwatershed boundaries within each HUC were derived from spatial data provided by the USVI DPNR. Offshore islands/cays were removed from the subwatershed polygons so that only the land area of each major island was included in the modeling analysis. A single outlet was defined within each subwatershed for evaluation of runoff volume and pollutant loading and no channel network was defined. Subwatershed land use was characterized from NOAA's Coastal Change Analysis Program (C-CAP) high-resolution land cover dataset (2007 series). C-CAP land cover classes were reclassified within SUSTAIN to define 7 land use groups; impervious, forest, wetland, open developed, open undeveloped, agriculture, and water (Table A-1). Reclassified groups represent distinct land uses with potentially varied runoff and pollutant contributions. To quantify the effects of human development on runoff and pollutant loading, separate simulations were configured for an "undeveloped" scenario, in which developed land use types were replaced with the dominant natural land use within each subwatershed.

**Table A-1. Land use types represented in SUSTAIN simulations and original C-CAP land cover classes.**

| SUSTAIN Land Use Group | C-CAP Land Cover Class |
|---|---|
| Impervious | Impervious |
| Agriculture | Cultivated Crops; Pasture |
| Open Developed | Developed Open Space |
| Open Undeveloped | Grassland; Shrub; Unconsolidated Shore; Bare Land |
| Forest | Deciduous & Evergreen Forest |
| Wetland | Palustrine & Estuarine Wetland Forest/Shrub/Grassland |

Meteorological input data included daily precipitation time series' from representative NCDC weather stations and daily evaporation. USVI precipitation records were reviewed for completeness and stations with missing data for greater than 10% of the period of analysis were not included in the modeling analysis. Five weather stations had sufficient rainfall data (Table A-2). Missing data for these stations were estimated using the normal-ratio method (estimates based on observed precipitation at nearby stations and long-term average values) (Dunn & Leopold, 1978). Daily precipitation was assumed to equal zero if no record existed for any station on the same island. Daily evaporation was estimated from daily temperature records and Hamon's equation for potential evapotranspiration (PET) in the Watershed Data Management Utility (U.S. Environmental Protection Agency, 2001). Weather stations with missing data for greater than 10% of the period of analysis were not considered for PET estimates. Two weather stations had sufficient temperature data (Table A-2). Missing temperature values were estimated as previous-day values. Meteorological data from weather stations within or in closest proximity to each subwatershed were used as model input.

**Table A-2 Weather stations used for precipitation and temperature estimates in SUSTAIN simulations.**

| Station Name & ID | Island | Missing Rainfall Data | Missing Temperature Data |
|---|---|---|---|
| Christiansted Airport (670198) | St. Croix | 1% | 2% |
| East Hill (672560) | St. Croix | 8% | - |
| Coral Bay (671790) | St. John | 10% | - |
| Charlotte Amalie Airport (678905) | St. Thomas | 2% | 1% |
| Wintberg (679450) | St. Thomas | 3% | - |

Initial estimates of SUSTAIN land simulation parameters were derived from existing site-specific datasets and typical values reported in scientific literature (Table A-3). Select parameters were internally generated by SUSTAIN (e.g., subwatershed area and width). Others were estimated as part of the data collection process from spatial datasets (e.g.., subwatershed slope). The USDA NRCS Soil Survey Geographic Database (SSURGO) and Soil Data Viewer were used to quantify a number of surface and subsurface soil parameters. Surface soil parameters estimated from SSURGO data were quantified as spatially-weighted average values within each subwatershed. Subsurface soil parameters estimated from SSURGO data were evaluated over a depth of 1.5 feet from the land surface and were quantified as spatially-weighted average values for each major island. The selection of 1.5 feet as the subsurface soil depth was based on SSURGO restrictive layer depth data, which denoted the presence of a shallow layer of low-permeability soil throughout the USVI land area. Site-specific data and/or recommended values were not available for select parameters, and estimated values were evaluated and refined for these and other parameters through model calibration.

**Table A-3. Data sources and methods used for initial estimates of SUSTAIN parameters.**

| Parameter Group | Parameter | Source |
|---|---|---|
| Evaporation | Pan coefficient | Estimated as 1.0 |
| Subwatershed | Subwatershed area, width | Estimated from subwatershed shapefile |
| | Subwatershed slope | Estimated from DEM |
| Surface Runoff | Manning's n, impervious areas | SWMM Manual (Table A.6) |
| | Manning's n, pervious areas | SWMM Manual (Table A.6) |
| | Depression storage, impervious areas | SWMM Manual (Table A.5) |
| | Depression storage, pervious areas | SWMM Manual (Table A.5) |
| | % impervious w/ zero depression storage | SWMM Manual (p. 8) |
| Infiltration | Suction head | SSURGO soil data & SUSTAIN Manual (Table 3-8) |
| | Saturated hydraulic conductivity | SSURGO soil data |
| | Initial moisture deficit | Estimated as soil wilting point |
| Aquifer | Porosity, field capacity, wilting point | SSURGO soil data |
| | Saturated hydraulic conductivity | SSURGO soil data |
| | Macropore porosity | Estimated as porosity minus field capacity |
| | Conductivity and tension slope | Estimated as 0.01 in./hr |
| | Upper evaporation fraction | Estimated as 1.0 |
| | Lower evaporation depth | Estimated as aquifer depth |
| | Lower groundwater loss rate | SSURGO soil data |
| | Initial water table elevation | Estimated as 0 ft. |
| | Initial unsaturated zone moisture | Estimated as soil wilting point |
| Groundwater | Elevation of land surface above aquifer | SSURGO soil data |
| | Groundwater flow coefficient | Estimated as 0.0 |
| | Groundwater flow exponent | Estimated as 1.0 |
| Pollutants | TSS EMC, developed areas | EPA BMP Design Guide Vol. 2 (Table 4-7) |
| | TSS EMC, undeveloped areas | EPA BMP Design Guide Vol. 2 (Table 4-7) |
| | Fecal coliform EMC, developed areas | EPA BMP Design Guide Vol. 2 (Table 4-11) |
| | Fecal coliform EMC, undeveloped areas | EPA BMP Design Guide Vol. 2 (Table 4-11) |
| | TSS groundwater concentration | 0 mg/l |
| | Fecal coliform groundwater concentration | 0 mg/l |

## A.3 Model Calibration

Land simulation parameter estimates were refined through model calibration. Calibration of runoff volume and timing typically involves comparison of modeled values against streamflow measurements collected within modeled watersheds. A review of USVI streamflow records within the USGS National Water Information System revealed limited availability of streamflow data (4 gaging stations include continuous observations over the last decade). In such cases, model calibration is informed through the development and calibration of an analogous simulation l for a nearby gaged watershed. Here, a single gaged watershed from each major island was selected to serve as a reference for model calibration (Table A-4). Selection of suitable stream gaging stations was based on the period of record (daily streamflow data collected through 2003) and quality of data (no missing data values, minimal upstream flow alteration).

**Table A-4. Site information for calibration watersheds.**

| Watershed Name | Island | USGS Gage ID | Area (acres) | Calibration Period (Water Year) | Validation Period (Water Year) |
|---|---|---|---|---|---|
| Jolly Hill Gut | St. Croix | 50345000 | 1377 | 2000 – 2003 | 1997 – 1999 |
| Guinea Gut | St. John | 50295000 | 196 | 2002 – 2006 | 2000 – 2002 |
| Bonne Resolution Gut | St. Thomas | 50252000 | 336 | 2002 – 2006 | 2000 – 2002 |

SUSTAIN simulations were configured for calibration watersheds in the same manner as those developed for USVI HUCs. Watershed boundaries were delineated using topographic data and the location of stream gaging stations, and each calibration watershed was represented as a single subwatershed with no defined channel network. Land use data showed low to moderate development in the calibration watersheds (3-11% impervious cover; 1-2% developed open space), with natural vegetation dominating the landscape (Table A-5). Initial estimates of land simulation parameters for calibration watersheds were determined from methods/sources outlined in Table A-3. Meteorological data collected within calibration watersheds were not available, and data from nearby weather stations were used as model input. Daily evaporation estimates from weather stations in closest proximity to calibration watersheds were selected as input data. Rainfall estimates from multiple weather stations were used for each watershed during the calibration process in order to test the assumption that weather station proximity was the best indicator of rainfall data quality/applicability (i.e., the weather station used for rainfall data was treated as a calibration variable).

**Table A-5 Summary of land use in calibration watersheds.**

| SUSTAIN Land Use | Jolly Hill Gut (St. Croix) | Guinea Gut (St. John) | Bonne Resolution Gut (St. Thomas) |
|---|---|---|---|
| Impervious | 3% | 11% | 10% |
| Developed Open | 1% | 2% | 2% |
| Agriculture | 9% | - | - |
| Undeveloped Open | 21% | 3% | 3% |
| Forest | 66% | 84% | 85% |
| Wetland | - | - | - |
| Open Water | <1% | - | <1% |

Runoff calibration datasets consisted of streamflow data over a four year period from each gaging station (Table A-4). USVI streamflow is highly variable, and the use of multiple years of calibration data allows for calibration to a broad range of hydrologic conditions. The inability to simulate both rapid subsurface flow and delayed baseflow in SUSTAIN required calibration to baseflow-separated stormflow data. A digital filter baseflow-separation technique (Arnold & Allen 1999) was applied to separate streamflow data into stormflow and baseflow components. Following model configuration and execution, modeled stormflow data were assessed through a comparison of observed and modeled annual stormflow magnitude, monthly stormflow magnitude, and daily hydrographs. Two statistical measures of the similarity between observed and modeled monthly stormflow were employed, the square of the Pearson correlation coefficient (r-squared) and the Nash-Sutcliffe coefficient of efficiency (NSCE). Model parameters were adjusted to maximize hydrograph similarity, annual stormflow magnitudes, and r-squared and NSCE values for monthly stormflow. A summary of observed and modeled annual stormflow data for calibration watersheds is provided in Table A-6. Observed and modeled values of total stormflow over the calibration period match closely for Jolly Hill Gut and Bonne Resolution Gut (within 1 inch), and are within 8 inches for Guinea Gut. Similarity between observed and modeled stormflow for individual years is variable. Model fit statistics for monthly stormflow data are highest for Jolly Hill Gut (r-squared = 0.89; NMSE = 0.88) and lowest for Guinea Gut (r-squared = 0.81; NMSE = 0.71) (Figure A-1). Stormflow hydrographs (Figure A-2 through Figure A-4) illustrate a general agreement between the timing of flow events, though discrepancies between observed and modeled daily stormflow magnitudes are apparent.

**Table A-6 Observed and modeled annual stormflow and runoff coefficient for calibration watersheds over the calibration period.**

| Watershed/Water Year | Rainfall (inches) | Stormflow (inches) | | Runoff Coefficient[1] | |
|---|---|---|---|---|---|
| | | Observed | Modeled | Observed | Modeled |
| ***Jolly Hill Gut, St. Croix*** | | | | | |
| 2000 | 46.1 | 2.9 | 2.6 | 0.06 | 0.06 |
| 2001 | 28.3 | 0.3 | 0.6 | 0.01 | 0.02 |
| 2002 | 27.3 | 0.2 | 0.2 | 0.01 | 0.01 |
| 2003 | 24.0 | <0.1 | <0.1 | <0.01 | <0.01 |
| Total | 125.7 | 3.4 | 3.5 | 0.03 | 0.03 |
| ***Guinea Gut, St. John*** | | | | | |
| 2003 | 36.5 | 1.5 | 1.9 | 0.04 | 0.05 |
| 2004 | 58.2 | 22.0 | 14.7 | 0.38 | 0.25 |
| 2005 | 54.5 | 5.6 | 10.6 | 0.10 | 0.19 |
| 2006 | 50.6 | 14.7 | 8.9 | 0.29 | 0.18 |
| Total | 199.8 | 43.8 | 36.1 | 0.22 | 0.18 |
| ***Bonne Resolution Gut, St. Thomas*** | | | | | |
| 2003 | 36.5 | 1.4 | 2.5 | 0.04 | 0.07 |
| 2004 | 58.2 | 11.9 | 11.7 | 0.20 | 0.20 |
| 2005 | 54.5 | 4.3 | 5.7 | 0.08 | 0.10 |
| 2006 | 50.6 | 6.6 | 5.0 | 0.13 | 0.10 |
| Total | 199.8 | 24.2 | 24.9 | 0.12 | 0.12 |

[1]Ratio of annual stormflow to annual rainfall

Runoff parameters that were modified from initial estimates during model calibration generally belonged to the aquifer and groundwater parameter groups (Table A-7). The exception was the impervious runoff routing parameter, which describes the percentage of impervious runoff routed to pervious areas (versus that flowing directly to the watershed outlet). Calibrated values indicated that the majority of impervious runoff (80-90%) was routed to pervious areas in calibration watersheds. Calibrated parameters for each watershed reflected a system with high surface infiltration and rapid buildup and release of shallow subsurface water. The choice of weather station for rainfall estimates was found to significantly influence results, however, the weather station in closest proximity to each calibration watershed did not provide the best fit between observed and modeled stormflow. For example, the lowest error between observed and modeled stormflow for Guinea Gut, St. John, was found using rainfall data from the Charlotte Amalie Airport weather station on St. Thomas.

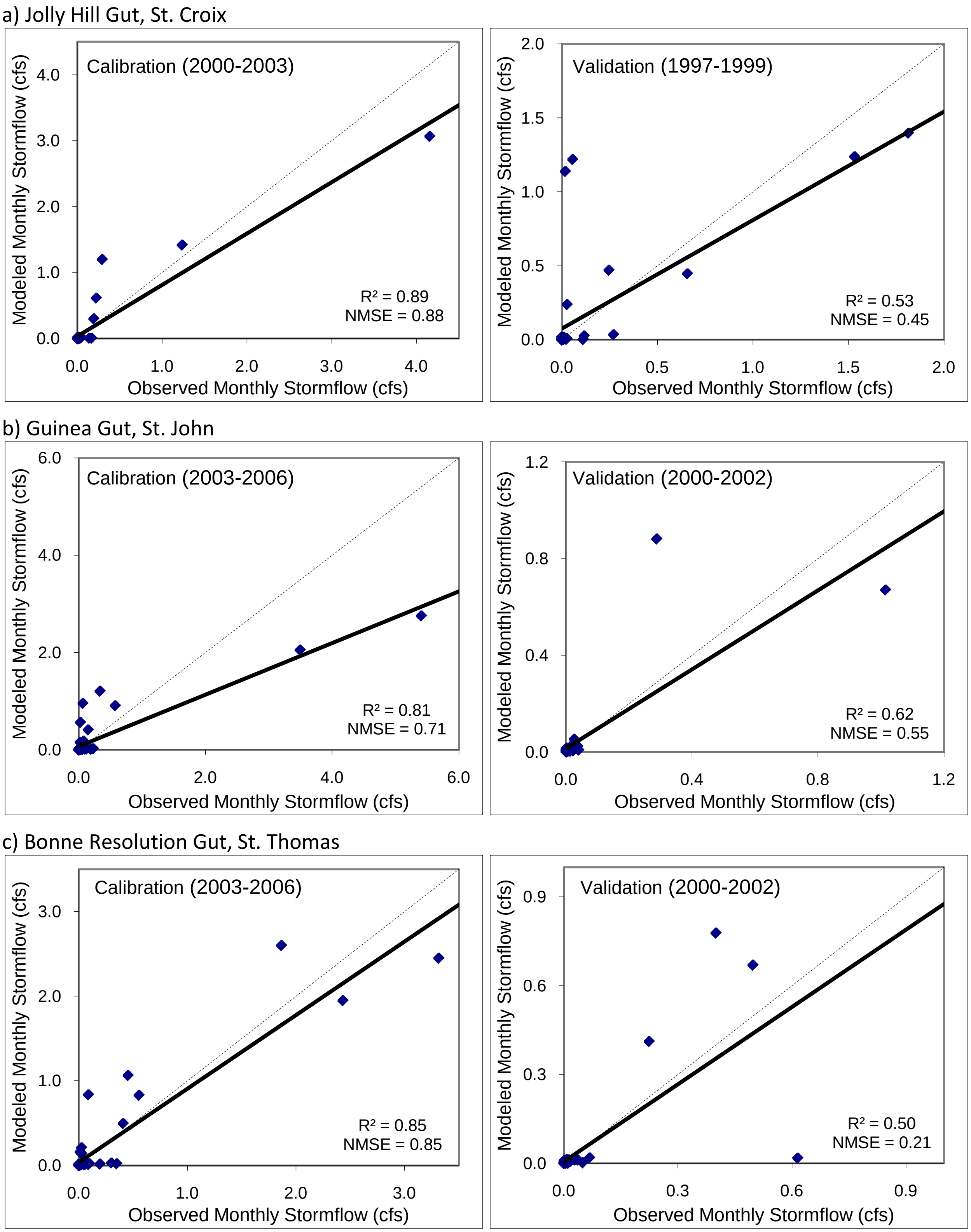


**Figure A-1. Observed and modeled mean monthly stormflow for each calibration watershed during calibration (left) and validation (right) periods.**

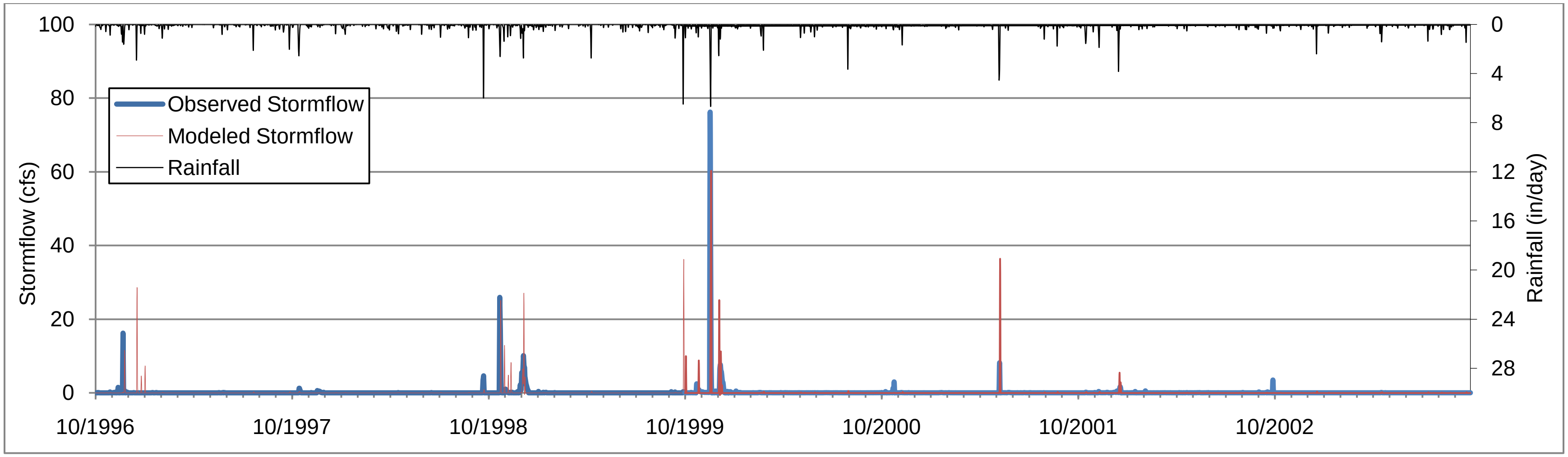


**Figure A-2. Stormflow hydrograph for Jolly Hill Gut, St. Croix for calibration (10/1/1999 – 9/30/2003) and validation (10/1/1996 – 9/30/1999) periods.**

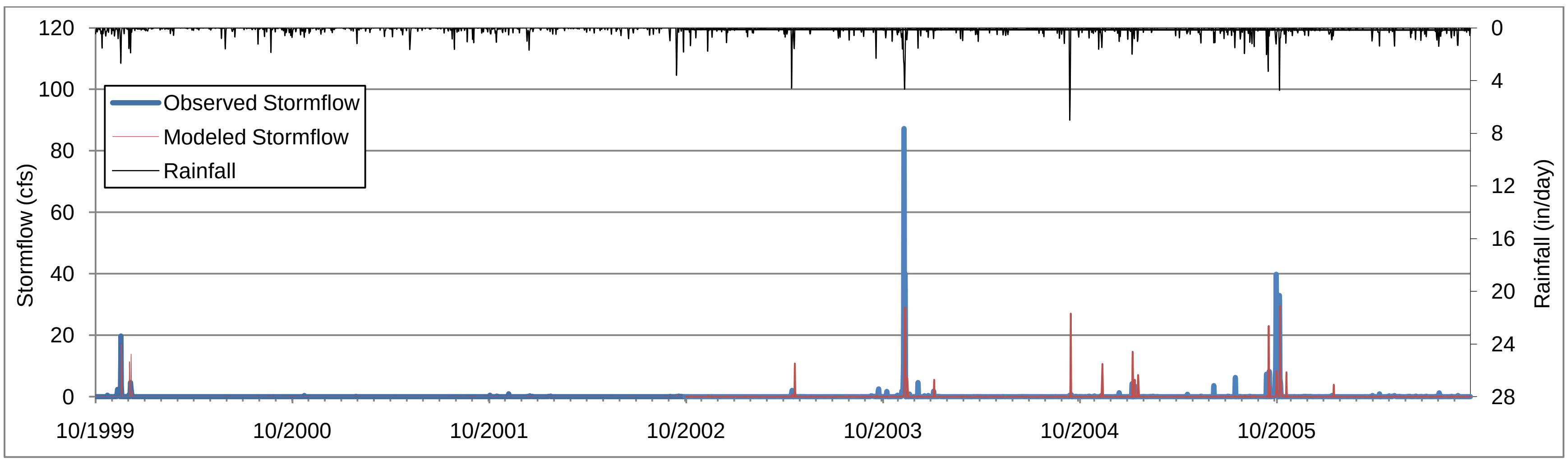


**Figure A-3. Stormflow hydrograph for Guinea Gut, St. John for calibration (10/1/2002 – 9/30/2006) and validation (10/1/1999 – 9/30/2002) periods.**

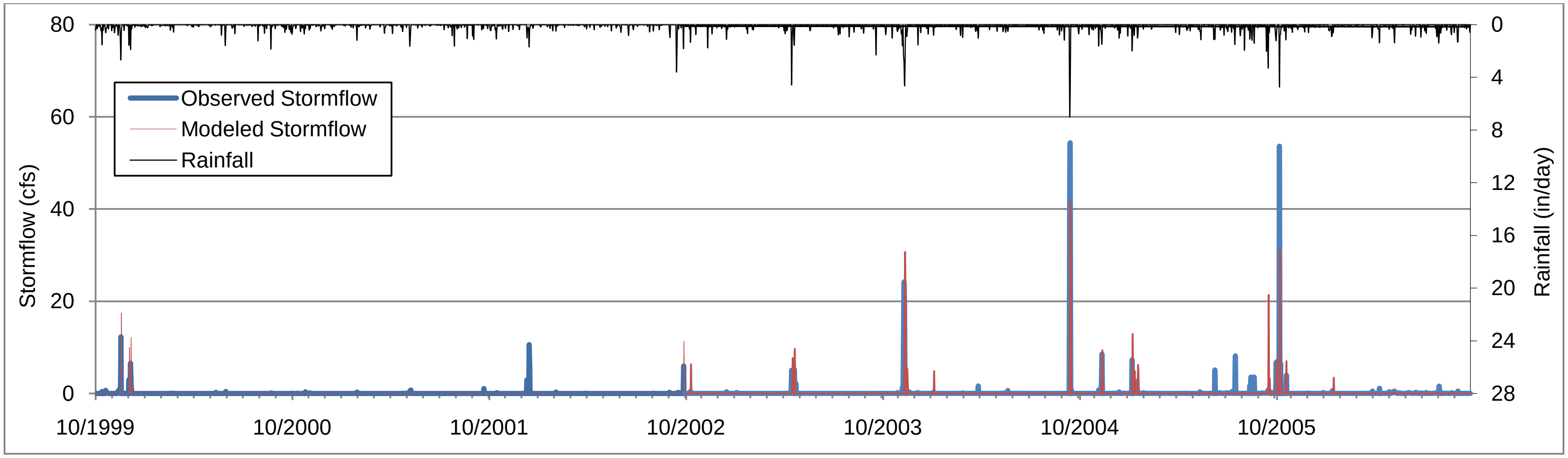


**Figure A-4. Stormflow hydrograph for Bonne Resolution Gut, St. Thomas for calibration (10/1/2002 – 9/30/2006) and validation (10/1/1999 – 9/30/2002) periods.**

**Table A-7. Calibrated parameter values for calibration watersheds. Values followed by (*) were modified from initial estimates during model calibration.**

| Parameter Group | Parameter | Calibrated Value | | |
|---|---|---|---|---|
| | | Jolly Hill Gut, St. Croix | Guinea Gut, St. John | Bonne Resolution Gut, St. Thomas |
| Evaporation | Pan coefficient | 1.0 | 1.0 | 1.0 |
| Subwatershed | Subwatershed area, width | 1377 ac, 2361 ft | 196 ac, 891 ft | 336 ac, 1166 ft |
| | Subwatershed slope | 25% | 30% | 33% |
| Surface Runoff | Manning's n, impervious areas | 0.011 | 0.011 | 0.011 |
| | Manning's n, pervious areas | 0.4 | 0.4 | 0.4 |
| | Depression storage, impervious areas | 0.1 in | 0.1 in | 0.1 in |
| | Depression storage, pervious areas | 0.3 in | 0.3 in | 0.3 in |
| | Impervious area w/ zero depression storage | 25% | 25% | 25% |
| | Impervious flow routed to pervious | 90%* | 80%* | 90%* |
| Infiltration | Suction head | 3.5 in | 8.3 in | 8.3 in |
| | Saturated hydraulic conductivity | 3.21 in/hr | 1.60 in/hr | 1.33 in/hr |
| | Initial moisture deficit | 0.09 | 0.07 | 0.09 |
| Aquifer | Porosity, field capacity, wilting point | 0.48, 0.09, 0.22* | 0.49*, 0.07, 0.23* | 0.46, 0.09, 0.21* |
| | Saturated hydraulic conductivity | 1.81 in/hr | 1.70 in/hr | 1.09 in/hr |
| | Macropore porosity | 0.26* | 0.25* | 0.25* |
| | Conductivity and tension slope | 0.01 in/hr, 0.01 in. | 0.01 in/hr, 0.01 in. | 0.01 in/hr, 0.01 in. |
| | Upper evaporation fraction | 1.0 | 1.0 | 1.0 |
| | Lower evaporation depth | 1.5 ft | 1.5 ft | 1.5 ft |
| | Lower groundwater loss rate | 0.7 in/hr* | 0.09 in/hr* | 0.5 in/hr* |
| | Initial water table elevation | 0 ft | 0 ft | 0 ft |
| | Initial unsaturated zone moisture | 0.09 | 0.07 | 0.09 |
| Groundwater | Elevation of land surface above aquifer | 1.5 ft | 1.5 ft | 1.5 ft |
| | Groundwater flow coefficient | 0.1* | 0.8* | 0.3* |
| | Groundwater flow exponent | 1.0 | 1.0 | 1.0 |
| Pollutants | TSS EMC, undeveloped areas | 26 mg/l | 26 mg/l | 26 mg/l |
| | TSS EMC, developed areas | 170 mg/l* | 117 mg/l | 117 mg/l |
| | Fecal coliform EMC, undeveloped | 100 CFU/100 ml | 100 CFU/100 ml | 100 CFU/100 ml |
| | Fecal coliform EMC, developed | 20,000 CFU/100 ml | 20,000 CFU/100 ml | 20,000 CFU/100 ml |
| | TSS groundwater concentration | 170 mg/l* | 80 mg/l* | 117 mg/l* |
| | Fecal coliform groundwater concentration | 15,000 CFU/100 ml* | 13,000 CFU/100 ml* | 20,000 CFU/100 ml* |

Long-term continuous water quality monitoring has not been conducted for USVI guts and observed water quality data were not available for calibration of pollutant parameters. Pollutant loading calibration instead included loading estimates generated by the Watershed Treatment Model (WTM) (Caraco, 2010). WTM is a spreadsheet-based annual loading model that has been applied to USVI watersheds as part of multiple TMDLs. WTM estimates of annual TSS and fecal coliform loads were derived for each calibration watershed from the "Primary Sources" worksheet using default WTM coefficients, watershed land use data, and annual rainfall data. A review of WTM output and algorithms indicated that the model was not appropriate for application to USVI watersheds for single-year analysis. WTM implicitly assumes that pollutant loads from undeveloped areas are constant over time and independent of runoff volume. Conversely, SUSTAIN's EMC algorithms account for the high degree of variability in USVI runoff, and modeled loads for low-flow years vary dramatically relative to estimated loads for high-flow years. Therefore, WTM and SUSTAIN pollutant load estimates were averaged over the calibration period, and years with negligible observed annual stormflow (<1 inch) were not included in analysis. Average WTM and SUSTAIN loading estimates were compared and SUSTAIN pollutant parameters were adjusted to minimize differences. Modeled and WTM-derived pollutant loads (Figure A-5) were within 10% of one another. Calibration of pollutant parameters generally involved increasing groundwater concentrations to reflect EMC values associated with runoff from developed areas (Table A-7).

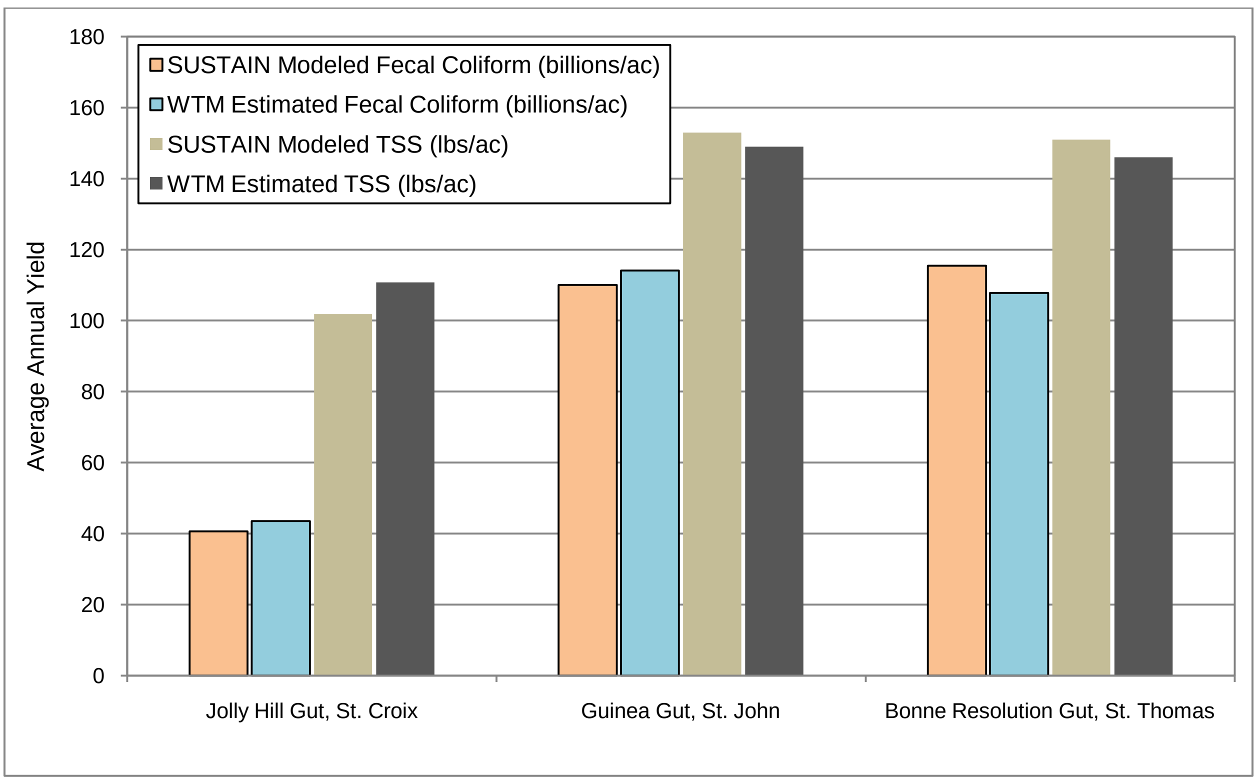


**Figure A-5. Average annual fecal coliform and TSS yield over the calibration period for each calibration watershed. Estimated loads were generated with the Watershed Treatment Model.**

## A.4 Model Validation

Calibrated hydrological models can be validated through a comparison of observations and model output for an alternative time period and/or location. Streamflow data from additional watersheds on each island were not available, and validation of SUSTAIN simulations for calibration watersheds was carried out by comparing observed and modeled stormflow for a separate validation period. For each calibration watershed, the 3-year period preceding the calibration period was selected for model validation (Table A-4). Annual stormflow values were well-predicted during the validation period for all calibration watersheds, with modeled annual stormflow within 1.1 inches of observed values for all years (Table A-8). Model fit statistics for monthly stormflow over the validation period declined relative to those obtained for the calibration period, and were highest for Guinea Gut (r-squared = 0.62; NSME = 0.55), and lowest for Bonne Resolution Gut (r-squared = 0.50; NMSE = 0.21) (Figure A-1). Modeled pollutant loads for the validation period were on the order of those derived from WTM, though modeled values were consistently lower than WTM estimates (Figure A-6). These differences are mainly a reflection of differences among the two models in methods used for load calculation rather than inaccuracy in calibrated model parameters.

**Table A-8. Observed and modeled annual stormflow and runoff coefficient for calibration watersheds over the validation period.**

| Watershed/Water Year | Rainfall (inches) | Stormflow (inches) | | Runoff Coefficient[1] | |
|---|---|---|---|---|---|
| | | Observed | Modeled | Observed | Modeled |
| ***Jolly Hill Gut, St. Croix*** | | | | | |
| 1997 | 34.9 | 0.4 | 1.0 | 0.01 | 0.02 |
| 1998 | 35.4 | 0.3 | 0.1 | 0.01 | <0.01 |
| 1999 | 45.2 | 1.9 | 2.3 | 0.07 | 0.08 |
| Total | 115.6 | 2.6 | 3.3 | 0.02 | 0.03 |
| ***Guinea Gut, St. John*** | | | | | |
| 2000 | 40.5 | 5.1 | 6.2 | 0.14 | 0.17 |
| 2001 | 30.0 | 0.1 | 0.3 | <0.01 | 0.01 |
| 2002 | 33.1 | 0.7 | 0.5 | 0.01 | 0.01 |
| Total | 103.5 | 5.9 | 7.0 | 0.03 | 0.03 |
| ***Bonne Resolution Gut, St. Thomas*** | | | | | |
| 2000 | 40.5 | 2.4 | 3.4 | 0.07 | 0.09 |
| 2001 | 30.0 | 0.4 | 0.2 | 0.01 | <0.01 |
| 2002 | 33.1 | 2.0 | 1.0 | 0.04 | 0.02 |
| Total | 103.5 | 4.8 | 4.6 | 0.02 | 0.02 |

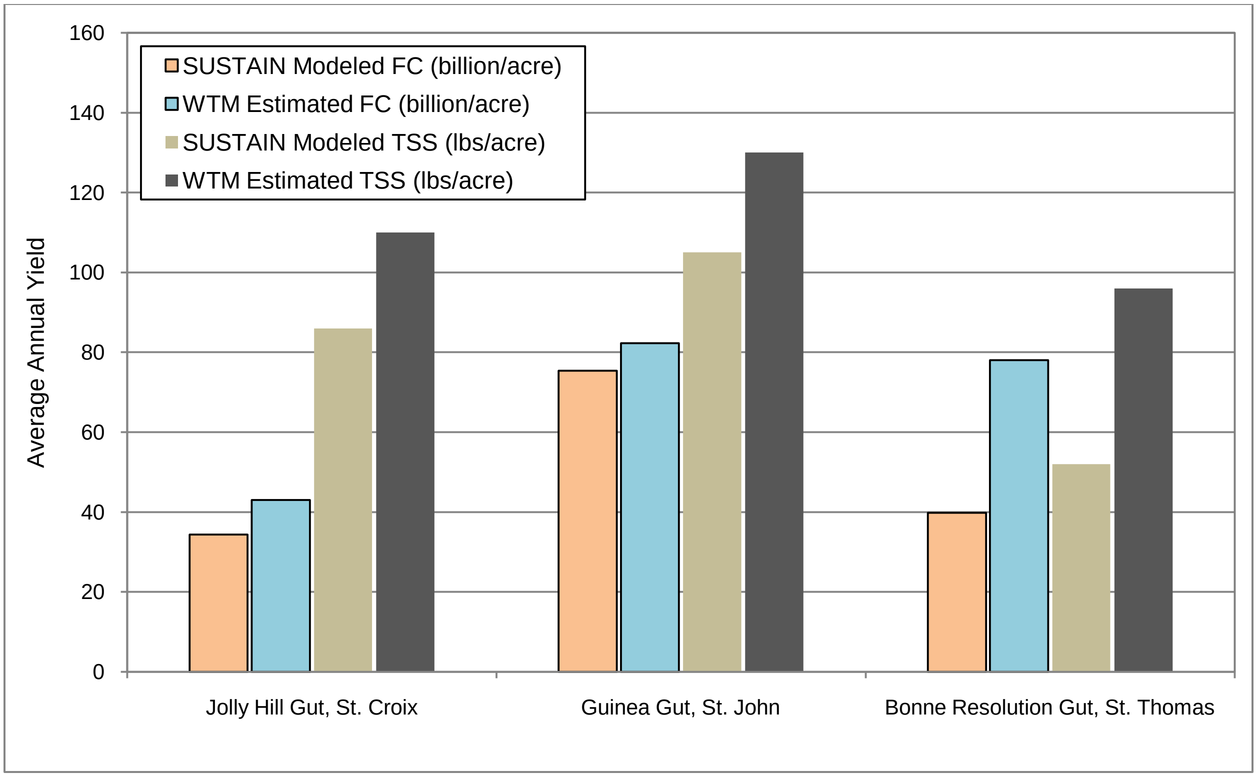


**Figure A-6. Average annual fecal coliform and TSS yield over the validation period for each calibration watershed. Estimated loads were generated with the Watershed Treatment Model.**

## A.5 Final Model Configuration and Application

Calibration and validation of SUSTAIN simulations for gaged watersheds indicated that SUSTAIN could be used to estimate storm runoff and pollutant loading in USVI HUCs with minor modifications to initial parameter estimates. Calibrated aquifer, groundwater flow, and pollutant parameter values developed for each calibration watershed were applied to all subwatersheds on the same island. Initial estimates of remaining parameters were not modified for HUC simulations. A source of uncertainty in SUSTAIN output is the estimated level of impervious to pervious runoff routing. Model calibration indicated that a high proportion of impervious runoff was routed to pervious areas in calibration watersheds. This property is likely variable for USVI subwatersheds and highly dependent on impervious surface extent, location, and existing drainage infrastructure. Final HUC simulations were configured with all impervious runoff routed directly to the subwatershed outlet in order to estimate maximum potential runoff volume and pollutant loads.

## A.6 Model Assumptions and Limitations

Error and uncertainty in the output of hydrological models result from a variety of sources. These generally relate to inaccuracies in model input data (notably in climatological inputs) and parameter estimates. USVI rainfall is highly variable by location, and site-specific rainfall estimates would likely improve model results. The high-resolution and high-quality nature of data used to quantify SUSTAIN parameters mitigates the potential for error resulting from parameter estimation, which is further reduced through model calibration/validation. However, the inability to compare model results with additional streamflow data and lack of water quality data for model calibration/validation introduces ambiguity to model output. Finally, assumptions made regarding the appropriateness of model algorithms to represent the modeled system can be a source of error and uncertainty. Each of these sources likely contributed to inconsistencies between observed and modeled runoff volume at daily to monthly scales. Observed annual values and totals over the entire calibration/validation periods are better predicted. Results of SUSTAN modeling for USVI HUCs are, therefore, presented as average values over the entire simulation period.