
APPENDIX D:

St. Thomas East End Reserve, St. Thomas, USVI Regional Model Development Report

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ACRONYMS AND ABBREVIATIONS

BOD	Biochemical Oxygen Demand
BOD5	Biochemical Oxygen Demand (5-day)
C-CAP	Coastal Change Analysis Program
DCIA	Directly Connected Impervious Area
DEM	Digital Elevation Model
DO	Dissolved Oxygen
DPNR	Department of Planning and Natural Resources (U.S. Virgin Islands)
ENTERO	Enterococcus
ET	Evapotranspiration
GIS	Geographic Information System
HRU	Hydrologic Response Unit
HSPF	Hydrologic Simulation Program--FORTRAN
ICIS	Integrated Compliance Information System
LiDAR	Light Detecting and Ranging
LSPC	Loading Simulation Program C++
MIA	Mapped Impervious Area
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NED	National Elevation Dataset
NHDPlus	National Hydrography Dataset Plus
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
QAPP	Quality Assurance Project Plan
QCLCD	Quality-Controlled Local Climatological Data
QGIS	Quantum Geographic Information System (software)
SOD	Sediment Oxygen Demand
SSURGO	Soil Survey Geographic database
STEER	St. Thomas East End Reserve
STORET	EPAs Storage and Retrieval System
STATSGO	State Geographic Database
STXEEMP	St. Croix East End Marine Park
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration Model
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Sediment
USDA	United States Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFS	United States Forest Service
USGS	United States Geological Survey
USVI	United States Virgin Islands
WAPA	Water and Planning Authority
WTM	Watershed Treatment Model
WQS	Water Quality Standards

1 PROBLEM DEFINITION AND MANAGEMENT OBJECTIVES

This document provides a summary of the methods and modeling approaches utilized in support of the Total Maximum Daily Load (TMDL) calculations for the waterbodies listed in Table 1-1. Details on the data used in developing the modeling extent and parameterization is presented and model calibration and verification results are included. This document is intended to be used as a supplement to the TMDL reports and the reader is encouraged to read each individual TMDL report for descriptions of the watersheds, project objectives, and results. This document explains the major steps, decisions, and assumptions made in the watershed modeling process. The STEER TMDLs were initially developed in parallel with other TMDLs on St. John and St. Croix. A regional modeling approach was used in which a model was set up and calibrated to provide consistent coverage of all three islands. While this modeling report focuses on STEER watersheds and waterbodies specifically, there are some elements of the model development process that are presented for watersheds outside of STEER (e.g., climate data in Section 4.3.1, calibration discussion in Section 5) due to the availability, or lack of, STEER specific data.

1.1 Background

Table 1-1 summarizes the waterbodies included on the United States Virgin Islands (USVI) 303(d) list of impaired waters requiring TMDLs. A variety of pollutants and impairment types are included, some of which can be directly related to water quality concentrations and some of which must be related via a surrogate target (i.e., Biochemical Oxygen Demand (BOD5), Total Nitrogen (TN) and Total Phosphorous (TP) loadings impacting Dissolved Oxygen (DO); Total Suspended Sediment (TSS) impacting Turbidity; and Enterococcus (ENTERO) as a surrogate for general indicator bacteria). The watershed model developed to support these TMDLs was set up based on our understanding of these systems, the major sources, and how pollutants are delivered to the waterbodies. Specific information on each of these impairments can be found within the TMDL reports.

Table 1-1. List of waterbodies included in this project and corresponding 303(d) listed constituents

Watershed	Waterbody ID	Waterbody Name	Dissolved Oxygen	Enterococcus Bacteria	Fecal Coliform	pH	Turbidity
St. Thomas East End Reserve (STEER)	VI-STT-25	Great Bay		●			
	VI-STT-28	Cowpet Bay		●			
	VI-STT-31	Nazareth Bay		●			
	VI-STT-33	Benner Bay					
	VI-STT-34	Benner Bay Lagoon Marina		●			●
	VI-STT-35	Mangrove Lagoon		●			●

2 CONCEPTUAL MODEL: KEY PROCESSES & VARIABLES

The primary objective of this study is to support TMDL calculations for implementation planning. Using all available data, this modeling approach quantifies flow and loads from anthropogenic and natural sources. The watershed model provides a high-resolution assessment of sources and loading potential. For TMDL calculation, the linkage analysis represents the essence of critical conditions associated with the TMDL impairment within the waterbody. This modeling approach uses a top-down weight of evidence approach to correlate the best-available information and corroborate findings across different layers of the analysis.

2.1 The Model Development Cycle

For TMDL analysis, the model development process can be a good platform for gaining valuable information and insight about a natural system. If well-designed, the model development process is an iterative and adaptive cycle that improves understanding of the natural system over time as better information becomes available. Ultimately, a model can inform future data acquisition efforts and management decisions by highlighting factors that have the most impact on the behavior of a natural system. Figure 2-1 is a conceptual schematic of a model development cycle. A well-designed model development cycle is conceptually circular as opposed to linear. That cycle can be summarized in six interrelated steps:

1. Assess Available Data: these data are used for source characterization, trends analysis, and defining modeling objectives
2. Delineate Project Extent: which refers to model segmentation and discretization
3. Set Boundary Conditions: including quality-controlled spatial and temporal model inputs
4. Represent Processes: refers to calibration of model rates and constants to mimic observed physical processes of the natural system
5. Confirm Responses: refers to validation of model processes over space and time to assess if the model is a robust predictive tool.
6. Assess Data Gaps: Sometimes the rigidity of modeled responses can highlight unrepresented physical processes in the natural system. Those data gaps sometimes provide a sound basis for further data collection efforts to refine the model, which cycles back to Step 1.

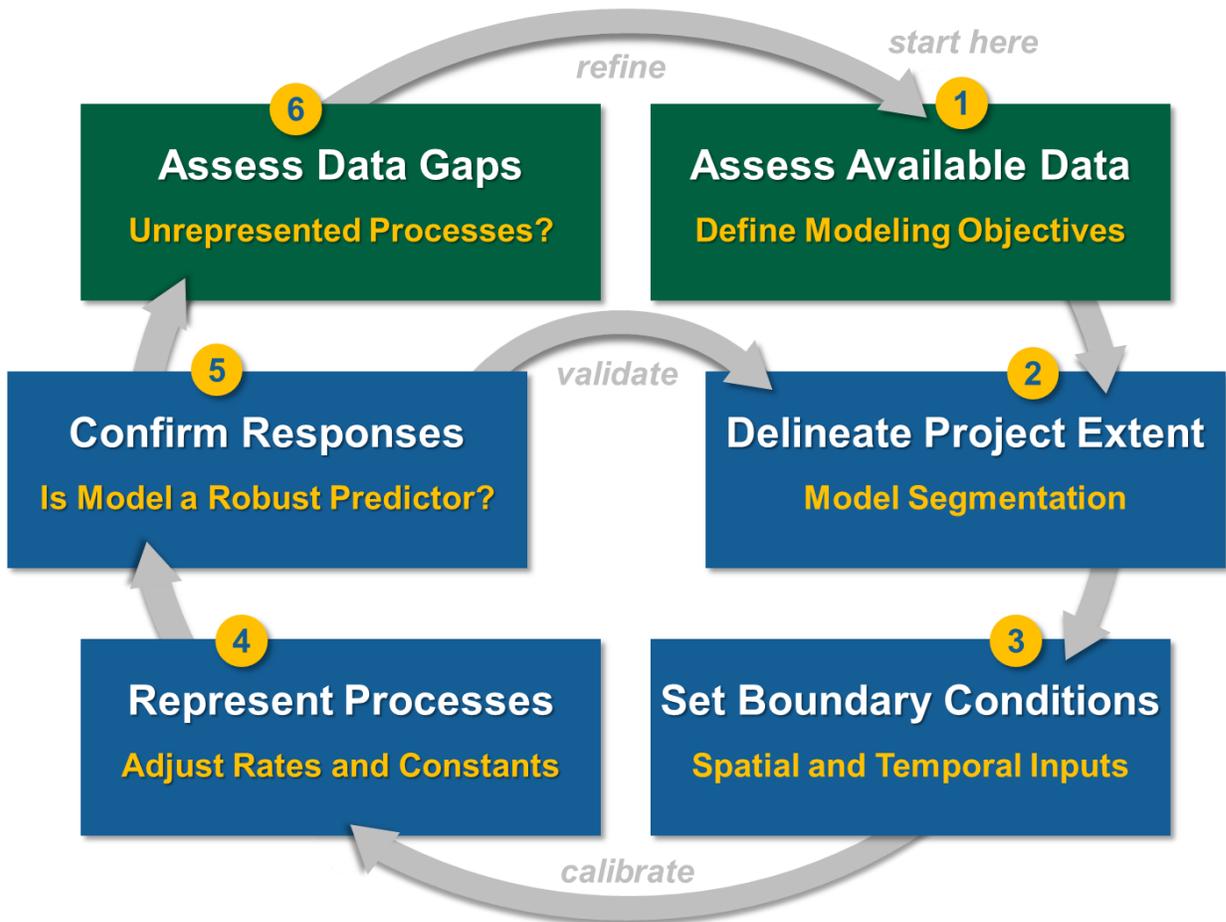


Figure 2-1. Conceptual schematic of a model development cycle.

3 TECHNICAL APPROACH

This section describes the models used as the scientific basis to establish current conditions and evaluate water quality-based controls to reduce pollution from both point and nonpoint sources and to restore and maintain the quality of the state's water resources (USEPA, 1991).

3.1 Watershed Modeling System

The hydrologic and water quality model applied for this TMDL was the Loading Simulation Program in C++ (LSPC), a watershed modeling system that includes Hydrologic Simulation Program–FORTRAN (HSPF) algorithms for simulating watershed hydrology, erosion, water quality processes, and in-stream fate and transport processes. LSPC integrates Geographic Information System (GIS) outputs, comprehensive data storage and management capabilities, the original HSPF algorithms, and a data analysis/post-processing system into a convenient PC-based Windows environment. The algorithms of LSPC are identical to a subset of those in the HSPF model with selected additions, such as algorithms to address land use change over time. LSPC is a public domain watershed model originally made available through United States Environmental Protection Agency's (USEPA's) Office of Research and Development in Athens, Georgia as a component of USEPA's National TMDL Toolbox. Some of the most recent advancements and applications of LSPC are in the Los Angeles, California Region (<http://dpw.lacounty.gov/wmd/wmms/>).

Simulation of upland loading and transport of sediment and nutrients was conducted to develop estimates of the relative contribution of pollutants by source to support developing land-based mitigation strategies. Three previous modeling efforts were reviewed and referenced for this study:

1. DO TMDL for Salt River Bay, St. Croix (DPNR, 2004). Continuous-simulation modeling using the LSPC watershed model.
2. Watershed Characterization and Planning for Pathogen Source Reduction in the USVI (Cadmus, 2011). Continuous-simulation modeling using the System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN).
3. St. Croix East End Watersheds Management Plan (Horsley Witten Group, 2011). Planning-level spreadsheet modeling using the Watershed Treatment Model (WTM).

The first two studies are process-based continuous simulation approaches that are capable of providing predicted flow and loading for a wide range of conditions that vary over space and time. Findings from those two studies provided directly applicable reference material for parameterizing and calibrating parameters associated with hydrologic and water quality processes, while the third provided locally derived model coefficients and long-term estimated source loads for benchmark comparison of simulated model results.

The hydrologic (water budget) model in LSPC simulates the stages of the water cycle for each Hydrologic Response Unit (HRU) segment, from rainfall on constructed landscapes, vegetation, and soil. Variations in interception storage, surface conditions, soil type, slope, length of overland flow, and other physical parameters influence the fate of water as it moves through the various layers of land, as applicable. Different HRUs will respond in different ways depending on how each is parameterized. Within the LSPC Model environment water exits the land segment and is routed to stream segments by up to three different flow pathways: surface runoff, interflow outflow, and/or groundwater outflow. Figure 3-1 presents a schematic of model inputs; storage compartments; transfers, losses, and interactions; and parameters (rates and constants).

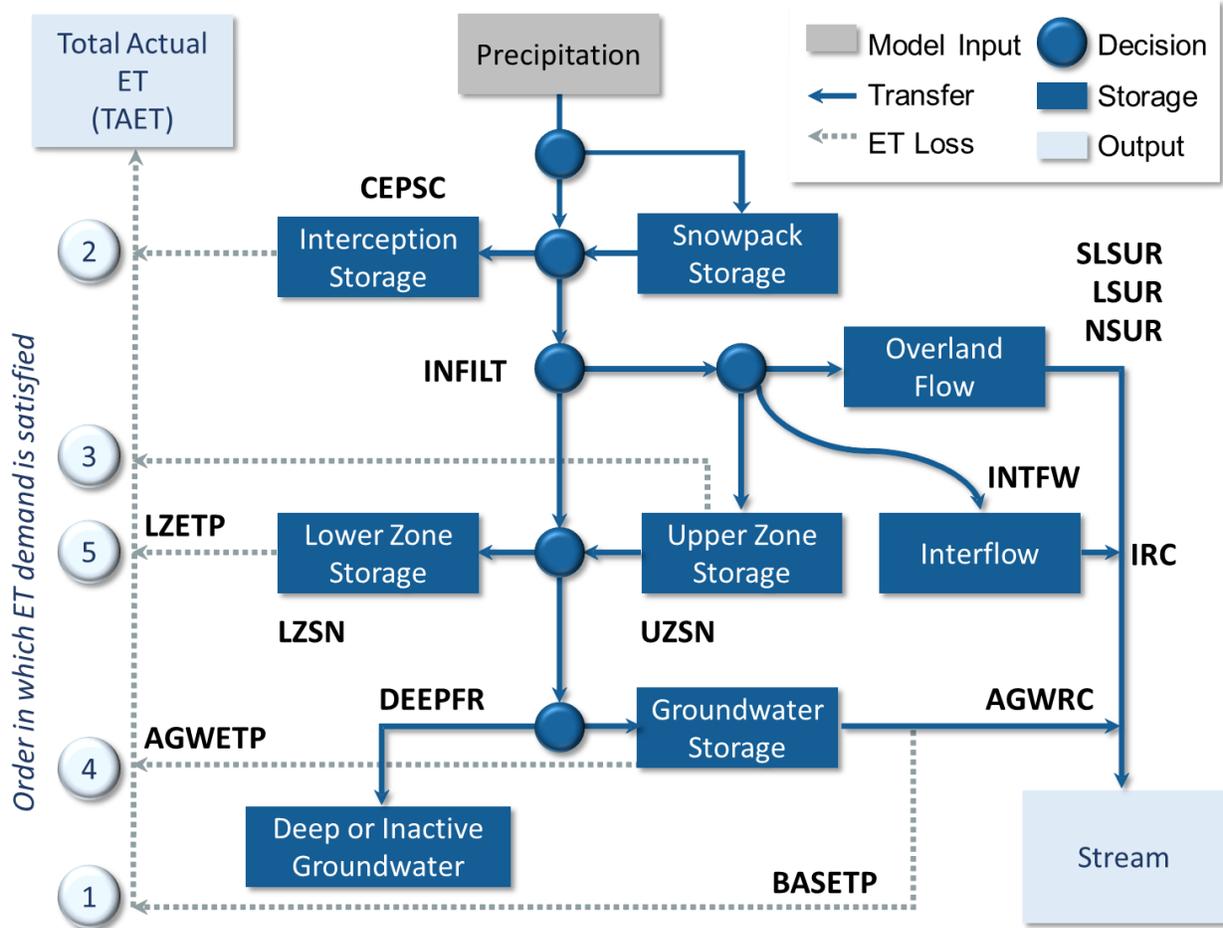


Figure 3-1. LSPC water budget schematic.

3.2 TMDL Mixing Model

The listed TMDL segments are coastal estuarine waterbodies. Observed data for water quality were collected at different stations within the waterbodies, but not upstream in the watershed. The spatial and temporal range of observed data represent different mixing conditions in each of the waterbodies, with some waterbodies providing a higher dilution potential than others. The objective of the TMDL is to capture the critical condition associated with the impairment and express representative daily load and waste load allocations for implementation planning.

A review of locally developed TMDLs showed that several of the DO TMDLs include Sediment Oxygen Demand (SOD) loading as a significant source of the impairment (St. Thomas Harbor, Vessup Bay and Red Hook Bay, Mangrove Lagoon, Benner Bay Lagoon Marina, and Benner Bay, St. Thomas; North Shore, and Salt River Bay, St. Croix). SOD represents an accumulation of loads from contributing sources at one point in time that affects water quality conditions at a later point in time. USVI is in a region of the planet where tidally influenced mixing is low. Upwelling and wind-driven storm mixing are the primary drivers of water exchange within the estuarine waterbodies. Building upon insights gained from previous regional TMDL modeling efforts, along with trends analysis to characterize critical conditions associated with water quality impairments, a simple mixing model was applied to represent critical conditions and calculate daily loads from contributing sources for the TMDL.

3.2.1 Conceptual Model

At the core of all hydrodynamic and water quality models are the fundamental concepts of continuity and mass balance. Previous modeling efforts have demonstrated the complex interactions associated with dilution and mixing, reactions and transformations. For mass balance of conservative substances in estuarine conditions, the continuity equation to characterize mixing takes the following form:

$$Q_{in}S_0 + Q_fS_f = Q_{out}S_1$$

where:

- Q_{in} = Oceanic Inflow
- S_0 = Oceanic salinity
- Q_f = Freshwater inflow
- S_f = Freshwater salinity (generally, $S_f = 0$)
- Q_{out} = Outflow to the ocean
- S_1 = Outflow salinity

Commonly used indicators of estuary health include residence time and exposure time. Residence time represents the time it takes for a water drop to leave the estuary, while exposure time represents the time a drop spends in the estuary until it never returns (which accounts for water that re-enters the estuary during ebb/flow cycles). A well-flushed estuary generally has better water quality than a poorly flushed estuary. Residence time (T) is expressed as:

$$T = \frac{Vol}{Q_f} \left(1 - \frac{S_1}{S_0} - \frac{S_f}{S_0} \right)$$

where:

- Vol = Volume of estuary within estuary
- Q_f = Freshwater inflow
- S_0 = Oceanic salinity
- S_f = Freshwater salinity (generally, $S_f = 0$)
- S_1 = Outflow salinity

Exposure time (t) is expressed as:

$$t = \frac{\overline{Vol} \times T_{tide}}{(1 - r)V_{TP}}$$

where:

- \overline{Vol} = Mean volume of estuary
- T_{tide} = Tidal period
- r = Return coefficient ($r=1$, all re-enters; $r=0$, none re-enters)
- V_{TP} = Mean tidal prism volume

As shown in Figure 3-2, the Caribbean is located at an amphidromic point on the Earth, meaning that it experiences high tide all the time; so effectively, there is negligible tide because the water level is nearly constant. Amphidromic points are the dark blue areas shown in Figure 3-2 where the white lines converge. Because the tidal period and volume of tide are less applicable to the Caribbean, the major factors affecting exposure time are the volume of water in estuary (Figure 3-3) and the return coefficient (which is a value between 0 and 1). Some physical factors that influence both residence time and exposure time are:

1. The width (or narrowness) of the estuary opening relative to its shoreline perimeter
2. The size of the watershed/drainage area (i.e., freshwater inflow volume)
3. The orientation of the estuary's opening relative to upwelling or wind-driven ocean currents

4. Bathymetric features or obstructions (e.g. sills, corals, other islands)

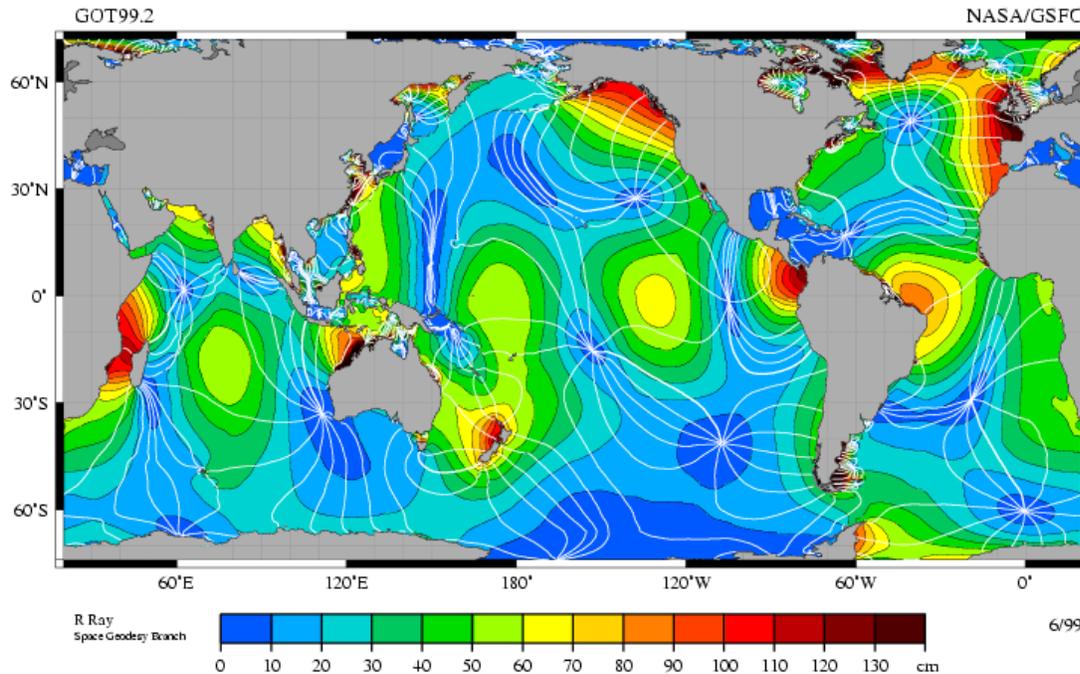


Figure 3-2. Global tidal variation (Source: Dr. Richard Ray/Space Geodesy branch, NASA/GSFC, NASA: http://svs.gsfc.nasa.gov/stories/topex/images/TidalPatterns_hires.tif)

After the existing condition was established, load allocations were applied to individual sources until modeled concentrations achieved target concentrations for the TMDL. TMDL calculation details, as well as summary tables with TMDL information for each listed waterbody and constituent, are included in the respective TMDL documents for each of the watersheds.

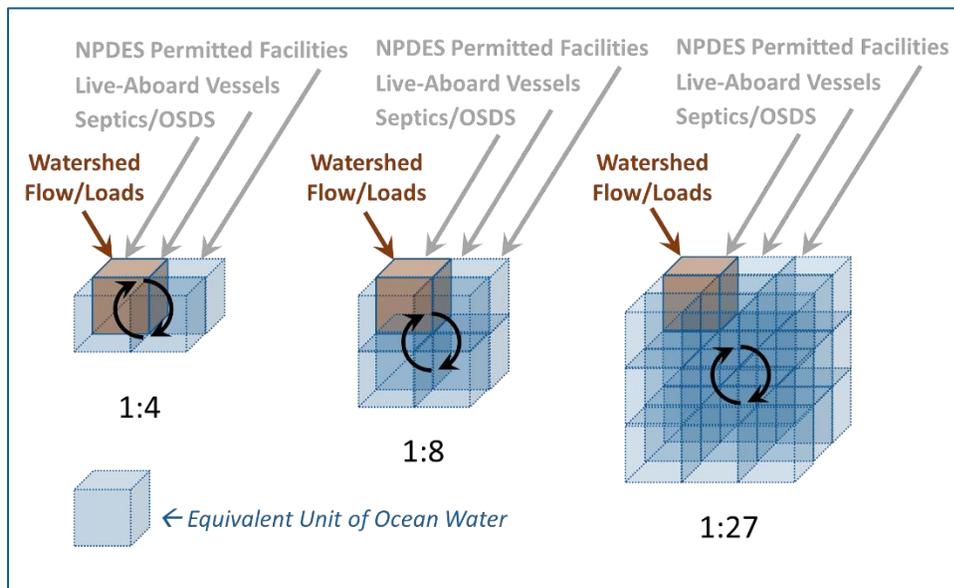


Figure 3-3. Conceptual model for estimating critical-condition mixing volume for each water body.

4 MODEL DEVELOPMENT

4.1 Hydrologic Response Units

An HRU is the smallest spatial unit in the model. Each HRU represents areas of similar physical characteristics attributable to certain processes. Spatial or geological characteristics such as land use, soils, and slopes are typically used to define HRUs. This section describes each of the component layers and the overlay process used to derive the HRUs.

4.1.1 Land Use/Land Cover

Land use/land cover data are the primary layers that form the basis for HRUs. The primary sources of land use/land cover for this effort were the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP) Regional Land Cover layer (NOAA, 2015) to represent most land cover categories, and the TIGER/Line roads layer (USCB, 2014) for added spatial resolution in representing roads. Figure 4-1 **Error! Reference source not found. Error! Reference source not found.** shows NOAA land use coverage (top panel) and NOAA pervious/impervious cover with TIGER roads overlay (bottom panel) for St. Thomas. summarizes the composite land use distribution within TMDL watersheds.

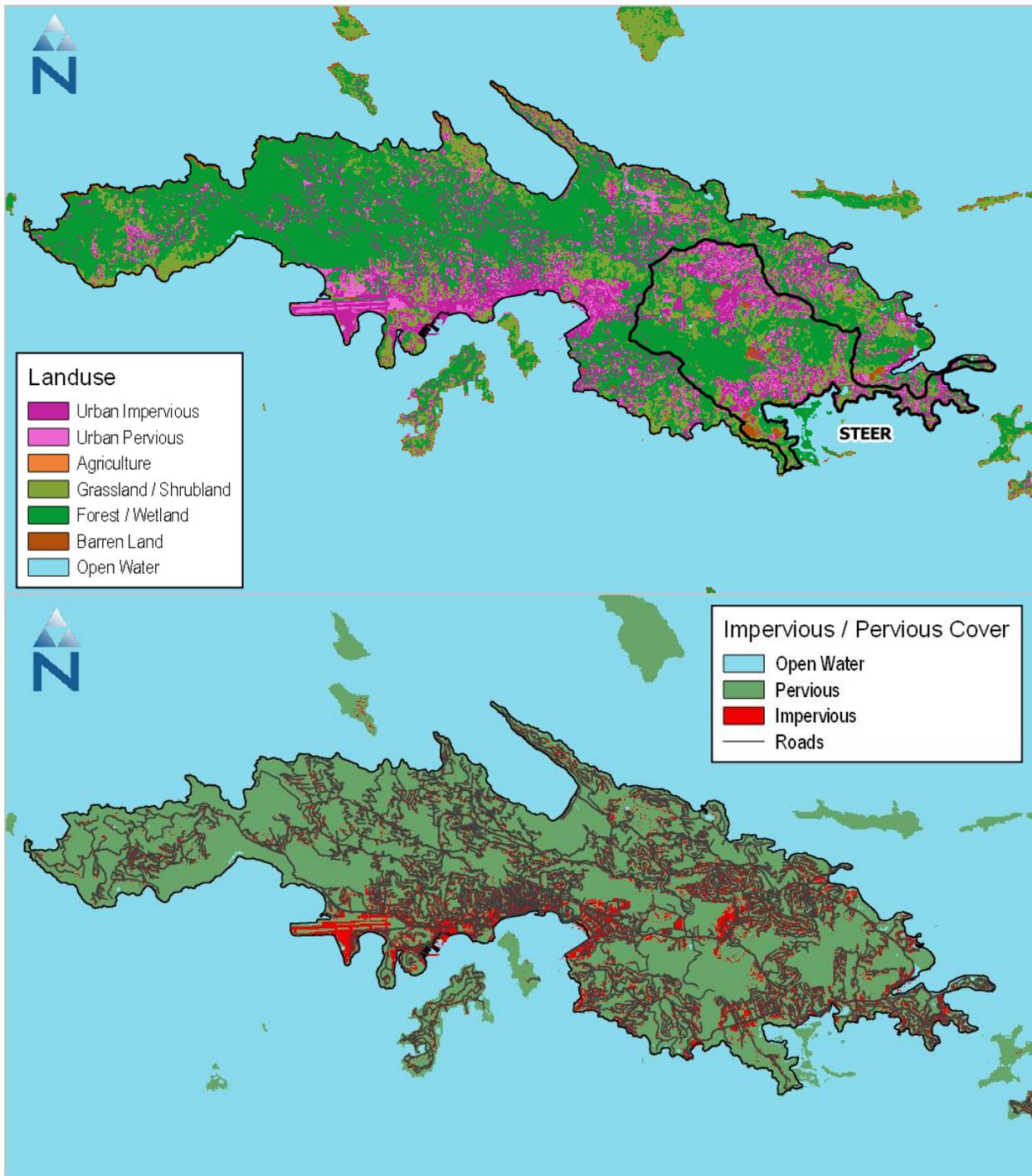


Figure 4-1. NOAA 2015 C-CAP land use/land cover (top panel) and NOAA pervious/impervious cover with TIGER Census roads layer (bottom panel) for Saint Thomas, USVI.

Table 4-1. Composite land use categories and model groups (Source: 2015 NOAA C-CAP)

Model Groups	Land Use Category	Area (acres)	Percent
Roads	Impervious Roads	1,136.06	4.0%
Urban Impervious	Impervious	1,571.06	5.6%
Urban_Pervious	Developed, Open Space	2,173.88	7.7%
Agriculture	Cultivated Crops	249.29	0.9%
	Pasture/Hay	1,921.24	6.8%
Grass_Shrub	Grassland/Herbaceous	718.64	2.6%
Forest	Deciduous Forest	9,078.06	32.3%
	Evergreen Forest	1,184.91	4.2%
Grass_Shrub	Scrub/Shrub	8,748.85	31.1%
Wetland_Palustine	Palustrine Forested Wetland	273.42	1.0%
	Palustrine Scrub/Shrub Wetland	2.37	0.0%
	Palustrine Emergent Wetland	25.47	0.1%
Wetland_Estuarine	Estuarine Forested Wetland	221.46	0.8%
	Estuarine Scrub/Shrub Wetland	63.83	0.2%
	Estuarine Emergent Wetland	5.88	0.0%
Barren	Unconsolidated Shore	76.17	0.3%
	Bare Land	313.33	1.1%
Water_Open	Open Water	341.01	1.2%
Total:		28,104.96	100.0%

4.1.2 Soils Data

Soils data for the watershed were obtained from the State Soil Geographic and Soil Survey Geographic Database (STATSGO/SSURGO). While the 2005 Summit to Sea Characterization of Coastal Watersheds - US Virgin Islands data set was also identified as a possible source, much of the soil-related information in this dataset was derived from SSURGO data; Therefore, the SSURGO and STATSGO data sets was used directly (NRCS 2016a, NRCS 2016b).

The SSURGO data set includes an attributed for hydrologic soil groups (HSG) used to characterize soil infiltration and runoff potential. This attribute is incorporated into the watershed model to parameterize infiltration. HSG is divided into four primary categories using an A through D designation. HSG-A generally has the lowest runoff potential whereas HSG-D has the highest runoff potential. Some map units may contain a compound soil grouping containing multiple HSGs which will be reclassified using a conservative estimate of the lowest infiltrating of the HSGs.

The soils database is composed of a GIS layer of polygon map units, and a linked database with multiple tables with soil properties. The representative hydrologic soil group for each polygon (as determined in the STATSGO/SSURGO database) was obtained for each map unit from the *map unit aggregated attribute table* (MUAGGATT) in the database. Figure 4-2 is a map showing the STATSGO/SSURGO hydrologic soil groups for STEER. Next, the NOAA land use layer was overlaid on the soils layer to further differentiate land use categories by hydrologic soil group. Within a given subwatershed, areas of the same land use category can have different underlying hydrologic soil groups—two areas of the same land use category with different soils could exhibit different runoff

potentials. Table 4-2 summarizes land use area by model group, cross-tabulated with hydrologic soil group distribution.

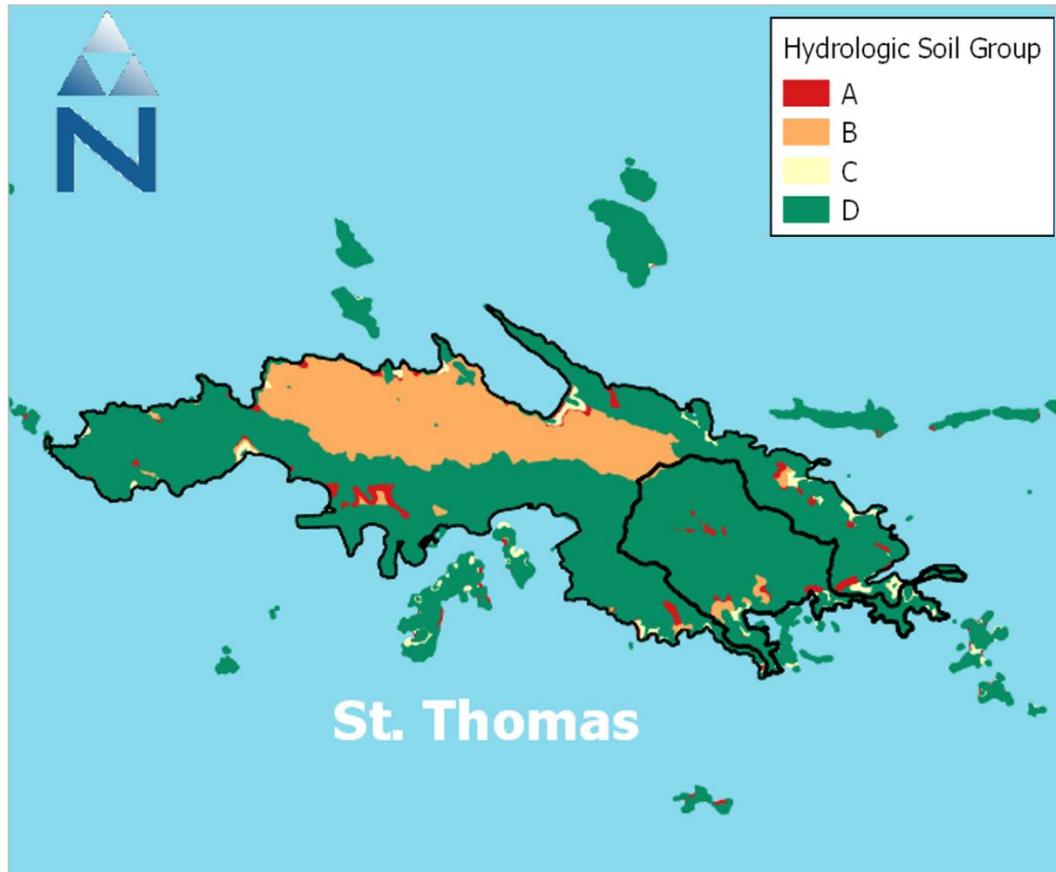


Figure 4-2. STATSGO/SSURGO hydrologic soil groups for St. Thomas, USVI.

Table 4-2. Land use and soils overlay (Source Data: 2015 NOAA C-CAP and STATSGO/SURGO Soils)

Model Groups	Area (acres)	Total	Hydrologic Soil Group				
			D	C	B	A	N/A
Roads_Impervious	1,136	4.0%	2.3%	1.5%	0.13%	0.08%	0.00%
Urban_Impervious	1,571	5.6%	3.5%	1.8%	0.17%	0.10%	0.00%
Urban_Pervious	2,174	7.7%	3.9%	3.3%	0.50%	0.06%	0.00%
Agriculture	2,171	7.7%	2.8%	4.5%	0.43%	0.01%	0.00%
Grass_Shrub ¹	9,467	33.7%	13.7%	18.1%	1.74%	0.13%	0.01%
Forest ¹	10,263	36.5%	22.8%	11.4%	1.99%	0.31%	0.00%
Wetland_Palustine	301	1.1%	0.1%	0.5%	0.14%	0.29%	0.00%
Wetland_Estuarine	291	1.0%	0.7%	0.2%	0.01%	0.03%	0.01%
Barren	390	1.4%	1.0%	0.3%	0.01%	0.06%	0.03%
Water	341	1.2%	0.7%	0.1%	0.00%	0.02%	0.45%
Total	28,105	100.0%	51.5%	41.8%	5.12%	1.09%	0.5%

1: Red Box highlights predominant land uses that were further subdivided by Hydrologic Soil Group.

The overlay summary showed that 93 percent of the study area was composed of either C or D soils. Soil Groups A, B, and unclassified (N/A) made up the other 7 percent. Groups C and D combinations were kept as classified for Forest and Grass_Shrub; however, because the total area was relatively small in comparison to C and D, groups A, B, and N/A were consolidated into a single category to simplify the number of HRU combinations in the model. Soil group is not relevant when overlaid with impervious land use, so all soils for those areas were also consolidated into a single category based on land only. Likewise, the land use categories (Urban_Pervious, Agriculture, Wetland, Barren, and Water), which make up 20 percent of the study area (with most of the area –18 out of the 20 percent of study area—being in soil groups C or D), they were also consolidated by land use only. During model calibration, those areas were considered mixed soils that were parameterized to exhibit an average C/D soils response.

4.1.3 Slope

The United States Geological Survey (USGS) National Elevation Dataset (NED) 10-meter digital elevation model (DEM) was used to derive slopes for this analysis. Figure 4-3 shows NED elevation, while Figure 4-4 shows derived slopes. As was done with soils, land use was also overlaid with the DEM-derived slopes to further differentiate certain land use categories by slope where applicable. Table 4-3 is a summary of the land use and slope overlay for the TMDL watersheds. A threshold of 15 percent slope was used to differentiate land between high- and low-slope areas. Areas with slopes <15 percent were classified as “Low”, while areas with slopes \geq 15 percent were classified as “High.” Within the TMDL watersheds, 65 percent of the area had “High” slopes, while 35 percent had “Low” slopes. For this study, Grass_Shrub, Forest, and Urban land uses areas, which make up 62 percent of the study area, were further divided into High and Low slope categories. Grass_Shrub and Forest were subdivided because they represent most of the area, and Urban because it represents anthropogenic activity. Subdividing these categories added more resolution for characterizing variability in hydrologic and water quality process responses in the model.

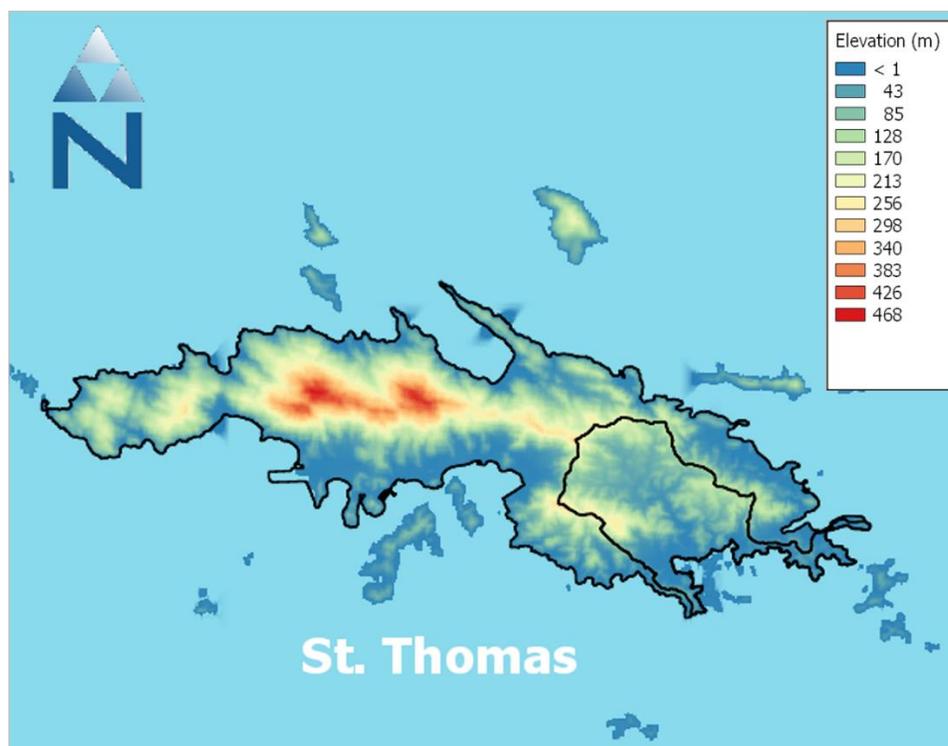


Figure 4-3. National Elevation Dataset coverage for St. Thomas, USVI.

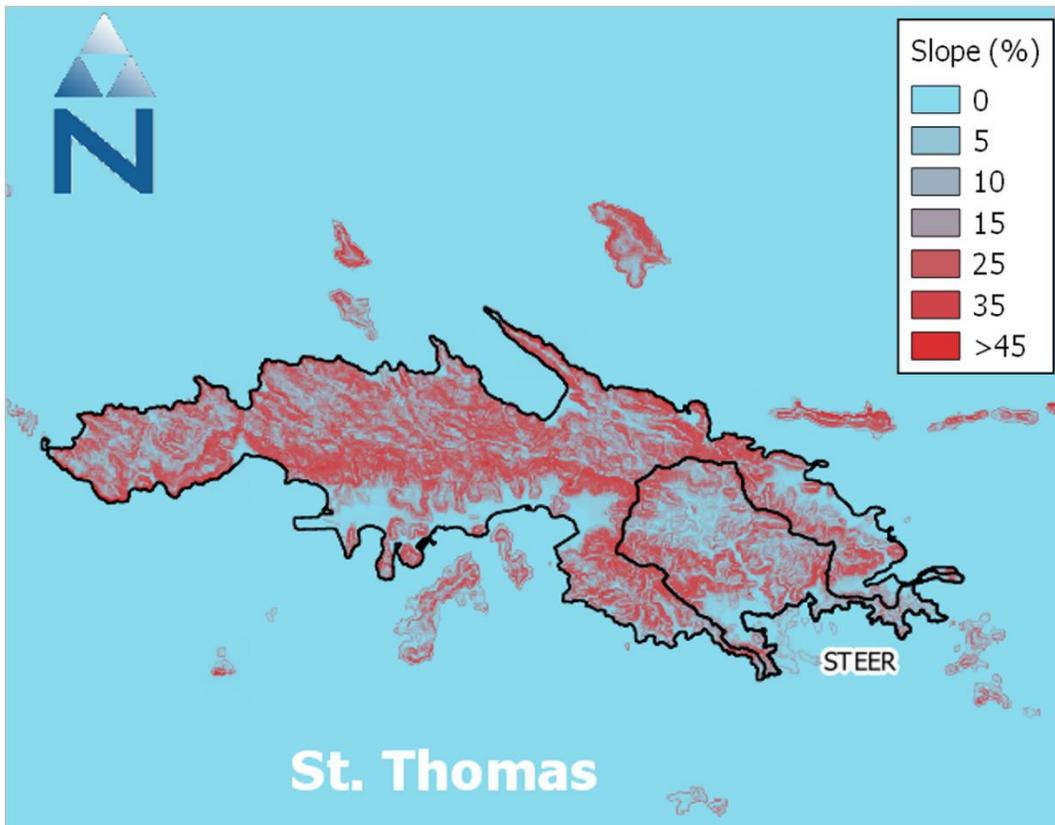


Figure 4-4. National Elevation Dataset slope coverage for St. Thomas, USVI.

Table 4-3. Land use and slope overlay (Source Data: 2015 NOAA C-CAP and NED DEM slopes)

Model Group	Area (acres)	Area		Average Slope	
		<=15%	>15%	<=15%	>15%
Roads	1,136	1.73%	2.32%	5.4%	14.6%
Urban_Impervious ¹	1,571	2.85%	2.74%	5.6%	13.3%
Urban_Pervious ¹	2,174	5.88%	1.86%	4.8%	12.6%
Agriculture	2,171	7.14%	0.59%	3.8%	14.3%
Grass_Shrub ¹	9,467	8.02%	25.67%	5.6%	16.2%
Forest ¹	10,263	5.06%	31.46%	5.1%	18.3%
Wetland_Palustine	301	1.03%	0.04%	3.1%	13.3%
Wetland_Estuarine	291	0.99%	0.03%	2.5	14.9
Barren	390	0.88%	0.51%	3.3	15.2
Water	341	1.03%	0.19%	3.6	11.1
Total	28,105	35%	65%	-	-

1: Red Box highlights predominant land uses that were further subdivided by slope.

4.1.4 Other HRU Refinements

Two other refinements were made to HRU layer to help characterize unique features that are important to characterizing water quantity and quality in the USVI: (1) rainwater harvesting and (2) construction. There were no specific layers identified that explicitly provided the information necessary; however, estimates could be derived from other supplemental supporting information and literature searches. These refinements are described in this section.

4.1.4.1 Rainwater Harvesting

Since the early 1930s, USVI has had mandatory laws requiring private residences and business to build cisterns for rainwater harvesting. The building code reenacted in 1964 and revised in 1996 has a clause requiring all dwellings not connected to municipal water supplies to construct cisterns for capturing, storing, and using rainwater for domestic water supply (Solomon, 2009). Customer service numbers from USVI Water and Power Authority (WAPA) show that 20 percent of residential households and less than 15 percent of businesses have water pipe connections. The other 80 to 85 percent of addresses rely on cistern water as their main source of domestic water (Solomon, 2009).

Because the purpose of this study is to support development of implementation plans, a higher-resolution Light Detecting and Ranging (LiDAR) dataset was used to refine assumptions about certain features on the landscape. LiDAR was used to differentiate rooftops impervious area from other urban impervious area. Because most of the rooftop runoff in USVI is used for domestic water supply, it is not available for watershed hydrology. Differentiating rooftop area from other impervious area makes it possible to quantify that volume of water and the role it plays in the water balance. On the basis of WAPA customer numbers, and estimated rooftop area, it was assumed in the model that 85 percent of rooftop water is not available for runoff because it is captured in cisterns for domestic use.

4.1.4.2 Construction Activity

Construction activity is typically one of the most impactful anthropogenic factors in a watershed. Figure 4-7 shows where the driveway of a typical construction site meets the main road in St. John. In most cases, it is a temporary activity that occurs for a season; however, while it is occurring, its impact can vary depending the quantity and quality of erosion mitigation measures that have been put in place. Although no spatial layers were identified that explicitly delineated construction activity, a rough estimate can be made by comparing land use changes between two snapshots in time: the 2007 and the 2012 NOAA C-CAT land use layers.

Table 4-4 summarizes land use change within the TMDL watersheds.

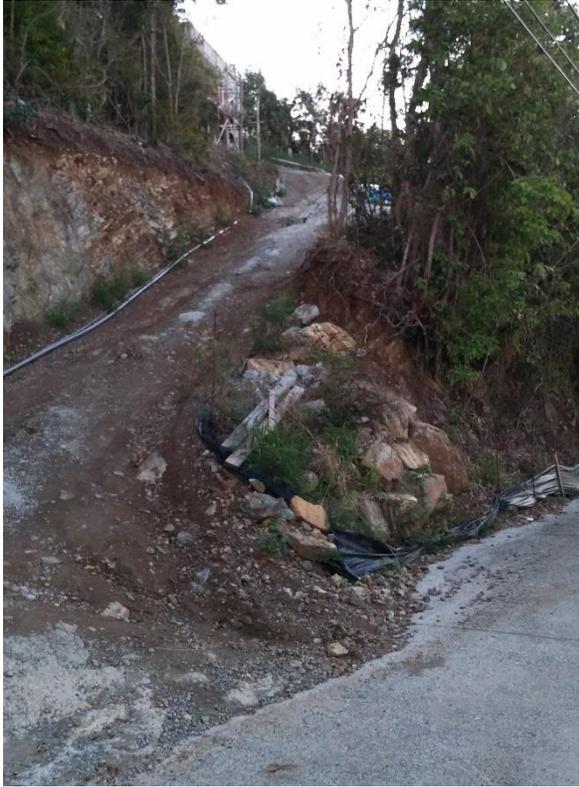


Figure 4-7. Example of failed sediment controls at a construction site (St. John, USVI 2016).

According to the NOAA C-CAT land use change dataset, about 985 acres in the TMDL watersheds changed from one category to another between the 2007 and 2012 snapshots. Changes in road area was not explicitly represented in this analysis because the TIGER/line roads layer captured one point in time—any new roads would be implicitly reflected among changes to “Urban” land use. Most “changing” area was Agriculture → Grass_Shrub or Agriculture → Forest, with some Grass_Shrub → Agriculture. Construction area was measured as a change from any undeveloped land use category to Urban. Some area classified as “Barren” in 2007 became “Urban” in 2012, suggesting that at any given point in time, some construction activity may be exhibited as “Barren” in the land use layer. The net change of area from any land use to “Urban” was about 220 acres, which represents a little less than 1 percent of the modeled study area. Changes were spatially tabulated by subwatershed as represented in the change layer; however, the temporal distribution is unknown. Assuming that construction is evenly distributed over the five years (2007-2012), with an average duration of a construction project as approximately one year, up to 20 percent of the changing area at any given time can be characterized as being under construction.

Table 4-4. Land use change matrix (Source Data: 2007 and 2015 NOAA C-CAP land use)

Changed From (2007)		Changed To (2012), acres ¹								
		Grass_Shrub	Agriculture	Barren	Forest	Urban Pervious	Urban Impervious	Water	Wetland_Palustine	Wetland_Palustine
Grass_Shrub	348	---	127	36	69	81	33	2	0	0
Agriculture	319	231	---	3	72	7	3	2	0	0
Barren	129	46	50	---	4	17	11	0	0	0
Forest	112	38	17	9	---	23	24	1	0	0
Urban Pervious	35	14	0	1	7	---	12	0	0	0
Urban Impervious	19	8	0	2	4	6	---	0	0	0
Water	21	0	0	0	0	0	0	---	3	18
Wetland_Palustine	2	0	0	0	0	0	2	0	---	0
Wetland_Estuarine	1	0	0	0	1	0	0	0	0	---
Total	985	337	194	52	156	134	87	5	3	18

1: Red Box areas that changed to urban from other land uses between 2007 and 2012.

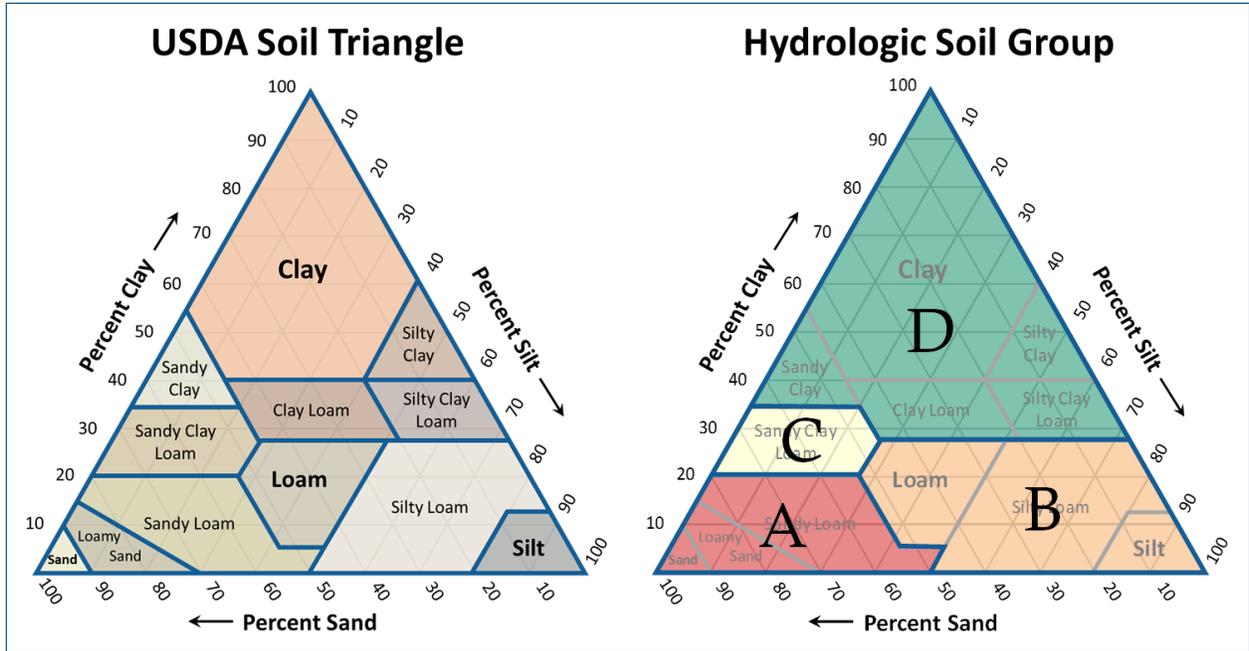


Figure 4-5. Standard United States Department of Agriculture (USDA) Soil Triangle with Hydrologic Soil Group mapping.

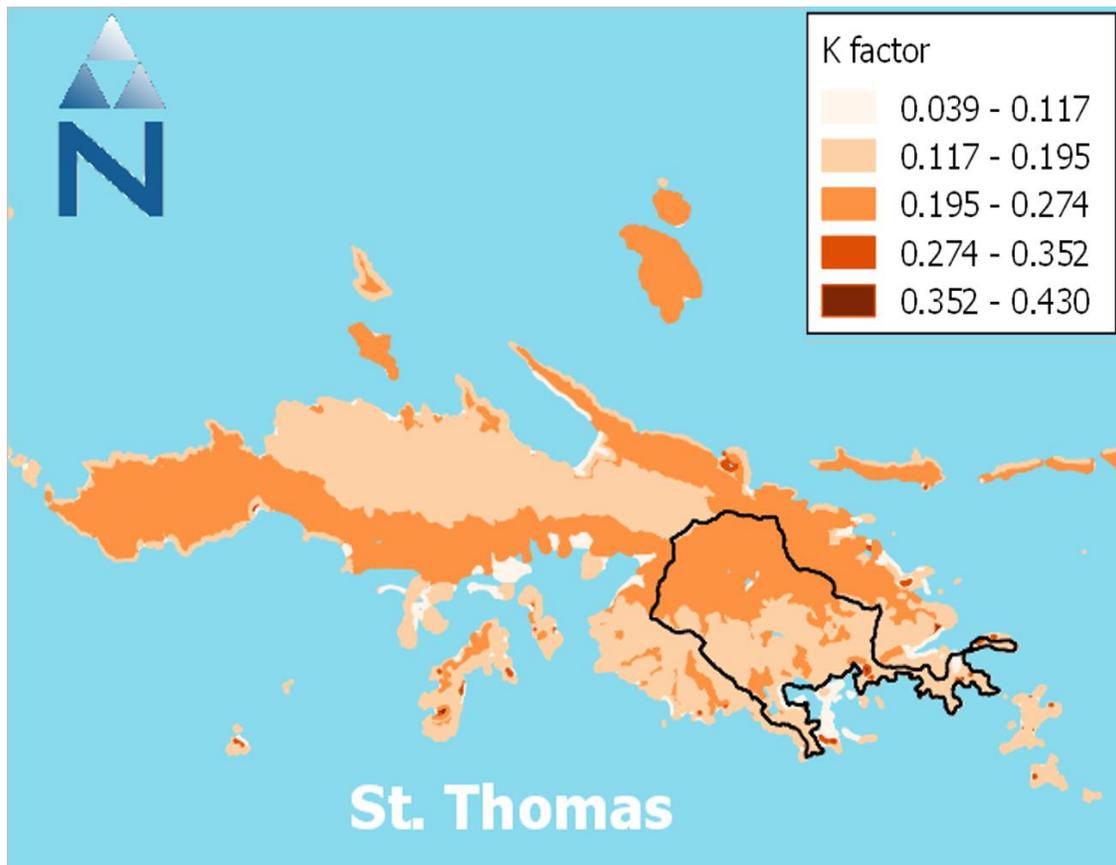


Figure 4-6. STATSGO/SSURGO K-Factor for St. Thomas, USVI.

4.1.4.4 Effective Impervious Area

Within a particular modeled subwatershed, HRU segments are modeled as being parallel to one another. Each segment flows directly to the routing segment without any interaction with neighboring segments. On physical landscapes, impervious land will flow downhill over pervious land en route to the watercourse on the landscape. For modeling purposes, Effective Impervious Area (EIA) represents the portion of total, or Mapped Impervious Area (MIA), that is directly-connected to the stream routing segments. Impervious areas that are not connected to the drainage network have the opportunity to flow onto pervious surfaces, infiltrate, and become part of pervious subsurface and overland flow. Because segments are modeled as being parallel to one another in LSPC, this process can be approximated using a conversion of a portion of impervious land to pervious land. On the open landscape, runoff from disconnected impervious surfaces can overwhelm the infiltration capacity of adjacent pervious surfaces during large rainfall/runoff events creating sheet flow over the landscape—therefore, the MIA→EIA translation is not actually a direct linear conversion. Finding the right balance between MIA and EIA can be an important part of the hydrology calibration effort.

An analogous parameter from the Cadmus 2011 SUSTAIN runoff modeling study is the fraction of impervious area that is directly-connected to a watercourse (DCIA). The complementary fraction of DCIA ($1 - DCIA$) is the amount of impervious area within a catchment that is first routed to pervious land before it reaches the watercourse. Among their three selected calibration watersheds, Cadmus assumed that between 80 and 90 percent of mapped impervious area is first routed to pervious area, meaning 10 to 20 percent is DCIA (Cadmus, 2011).

During model LSPC calibration for this study, a strong correlation was found between *density* of developed area and assumed DCIA, which was corroborated by improvements in model performance (reduction in the flashiness of storm peaks). Table 4-6 summarizes total, urban, MIA and EIA, along with calibrated DCIA ranges among the TMDL watersheds. The relationship between impervious density and DCIA was also intuitively reasonable because as developed area density increases in a subwatershed, so does the likelihood of that impervious area somehow being directly connected to a watercourse. Conversely, the less developed a subwatershed is, the potential impact of DCIA also becomes smaller.

Table 4-6. Mapped Impervious Area (MIA) vs. Effective Impervious Area (EIA) summarized by TMDL watershed

TMDL Watershed	Area (acres)				Average DCIA ²	Range of DCIA (by Subwatershed)				
	Total	Total Urban	MIA ¹	EIA ³		Min	25th	Median	75th	Max
STEER	3,715	1,182	820	261	32%	3%	17%	33%	40%	71%

1: Mapped Impervious Area (MIA)

2: Directly-Connected Impervious Area (DCIA) Percentage

3: Effective Impervious Area (EIA) = MIA × DCIA

4.2 Source Characteristics

TMDL critical conditions include both temporal and spatial influences. Four primary sources of pollutants were considered: (1) flow and loads from watersheds, (2) point source discharges, (3) septic system discharges, and (4) direct discharges from live-aboard vessels. Previous studies have characterized flow and loads from watersheds. These are shown in Table 4-7. For the temporal component, point sources and septic systems were modeled as constant while watershed and live-aboard vessel discharges varied monthly. For monthly variable sources, long-term continuous simulation loads from the watershed were aggregated and expressed as daily loads per month, while the estimated number of live-aboard vessel residents per month and per-capita boat effluent volume/loads were multiplied to estimate monthly loads from live-aboard vessels. For the spatial component, the critical-condition mixing volume was estimated as a ratio of total watershed flow to equivalent ocean water. This approach implicitly accounts for the influence of physical factors affecting the mixing efficiency of each waterbody.

Table 4-7. Summary of regional and national unit-area loads by land use (LU) from various literature sources

Pollutant	Source	Land use or Location of Study	Selected Model LU for Comparison	Minimum	Maximum	Units
ENTERO	East End Watersheds Management Plan (2011)	Forested	Forest	12	12	Billions/acre/yr
	East End Watersheds Management Plan (2011)	Rural	Grass	39	39	Billions/acre/yr
TSS	Ramos-Scharron (2010)	Parguera Disturbed	Construction	18	26,765	lbs/ac/yr
	East End Watersheds Management Plan (2011)	Forested	Forest	50	78	lb/acre/yr
	Ramos-Scharron (2010)	Parguera Undisturbed	Forest	1	45	lbs/ac/yr
	East End Watersheds Management Plan (2011)	Rural	Grass	100	127	lb/acre/yr
TN	Reckhow et al. (1980)	Non Row Crops	Agriculture	0.86	6.96	lb/ac/yr
	Dodd, R. C., McMahon, G. and Stichter, S. (1992)	Developed	Developed	4.45	8.65	lb/ac/yr
	Loehr, R. C., Ryding, S. O., and Sonzogni, W. C. (1989)	Residential	Developed	4.45	6.50	lb/ac/yr
	Loehr, R. C., Ryding, S. O., and Sonzogni, W. C. (1989)	Forest	Forest	0.89	5.61	lb/ac/yr
	Dodd, R. C., McMahon, G. and Stichter, S. (1992)	Forest/wetland	Forest	0.61	3.38	lb/ac/yr
	East End Watersheds Management Plan (2011)	Forested	Forest	2.50	2.51	lb/acre/yr
	Reckhow et al. (1980)	Forested	Forest	1.23	5.57	lb/ac/yr
	Loehr, R. C., Ryding, S. O., and Sonzogni, W. C. (1989)	Idle land	Grass	0.45	5.34	lb/ac/yr
	East End Watersheds Management Plan (2011)	Rural	Grass	4.60	4.61	lb/acre/yr
TP	Reckhow et al. (1980)	Non Row Crops	Agriculture	0.09	2.58	lb/ac/yr
	Dodd, R. C., McMahon, G. and Stichter, S. (1992)	Developed	Developed	0.40	1.34	lb/ac/yr

Pollutant	Source	Land use or Location of Study	Selected Model LU for Comparison	Minimum	Maximum	Units
	Loehr, R. C., Ryding, S. O., and Sonzogni, W. C. (1989)	Residential	Developed	0.69	1.96	lb/ac/yr
	Loehr, R. C., Ryding, S. O., and Sonzogni, W. C. (1989)	Forest	Forest	0.01	0.78	lb/ac/yr
	Dodd, R. C., McMahon, G. and Stichter, S. (1992)	Forest/wetland	Forest	0.08	0.19	lb/ac/yr
	East End Watersheds Management Plan (2011)	Forested	Forest	0.20	0.21	lb/acre/yr
	Reckhow et al. (1980)	Forested	Forest	0.02	0.74	lb/ac/yr
	Loehr, R. C., Ryding, S. O., and Sonzogni, W. C. (1989)	Idle land	Grass	0.04	0.22	lb/ac/yr
	East End Watersheds Management Plan (2011)	Rural	Grass	0.70	0.71	lb/acre/yr
BOD5	Mangrove Lagoon and Benner Bay DO TMDL (2003)	Agriculture	Agriculture	29	29	lb/acre/yr
	Mangrove Lagoon and Benner Bay DO TMDL (2003)	Residential (High Density)	Developed	26	26	lb/acre/yr
	Mangrove Lagoon and Benner Bay DO TMDL (2003)	Residential (Low Density)	Developed	14	14	lb/acre/yr
	Mangrove Lagoon and Benner Bay DO TMDL (2003)	Residential (Medium Density)	Developed	20	20	lb/acre/yr
	Mangrove Lagoon and Benner Bay DO TMDL (2003)	Urban	Developed	206	206	lb/acre/yr
	Mangrove Lagoon and Benner Bay DO TMDL (2003)	Parks/Recreation/Open Space	Grass	6	6	lb/acre/yr
	Mangrove Lagoon and Benner Bay DO TMDL (2003)	Undeveloped	Grass	6	6	lb/acre/yr

4.3 Data Availability and Quality

Data from a range of sources were collected and applied for model development. Table 4-8 presents a summary of the quantity and quality of available data that were used for model development. Many of these data sources are described further in context of how they were applied in this report. For example, meteorological (Appendix E), hydrology, and land cover data are key components of the watershed model. Other data sources not directly associated with the watershed are individually described in the context of their respective TMDL documents. Water quality data sheets are summarized in Appendix B and are considered again for the mixing model relative to corresponding watershed model loads. Surrogate pollutants were also identified for some of the TMDL listings, as described in this section. Supporting trends analysis for all listed pollutants are presented in Appendix C.

Table 4-8. Data quantity and quality inventory for model development

Supporting Information		Data Source	Data Type or Method		
Category	Information		Observed/ Digital	Literature/ Surveys	Estimated/ Empirical
Legend: ● Available, Comprehensive ◐ Available, Partial ○ Available, Deficient - Not Applicable or Available					
Weather	Precipitation	NCDC	◐		◐
	Temperature	NCDC	◐		◐
	Evapotranspiration	NCDC			◐
	Wind Speed	NCDC	◐		
Hydrology	Elevation	USGS DEM	●		
	Flow records	USGS Daily Flow Records	○		
	NHD	USGS NHD	●		
	Stream geometry	Estimated	◐		◐
	Soils	STATSGO/SSURGO	●		
Water Quality	Ambient monitoring	STORET	◐		
	Storm monitoring		-		
	Groundwater	USGS	◐		
	Land Use/Cover	NOAA C-CAP	●		
Hydraulics	Tidal information	NASA	-	-	-
	Bathymetry	NOAA	●		
Sources	Septic numbers/location	Census	◐		
	Point sources	NPDES ICIS	●		
	MS4	Census Urban Areas	◐		

Supporting Information		Data Source	Data Type or Method		
Category	Information		Observed/ Digital	Literature/ Surveys	Estimated/ Empirical
	Live-aboard vessels	Surveys		●	●
	Land Use Change	Land Use Layer	●		
	Road network	Census Tiger Roads	●		
	Tourism Rates	Bureau of Economic Research		●	●
	Building Permits	Bureau of Economic Research		●	●

4.3.1 Meteorological Data

Meteorological data are a critical component of the watershed model. They are the forcing functions that drive both hydrology and associated water quality responses. For modeling Caribbean climate conditions, precipitation and evapotranspiration are required at a minimum. In general, hourly (or finer-resolution) precipitation data are recommended for simulating hydrology, erosion, and water quality processes in LSPC. The two primary data sources of observed weather data evaluated and processed for modeling were: (1) the National Climatic Data Center (NCDC) Global Historic Climatology Network (GHCN) daily gage network (30 gages) and (2) the NCDC Quality Controlled Local Climatological Data (QCLCD) hourly gage network (2 gages). Figure 4-7 shows the location of NCDC meteorological stations in the USVI.

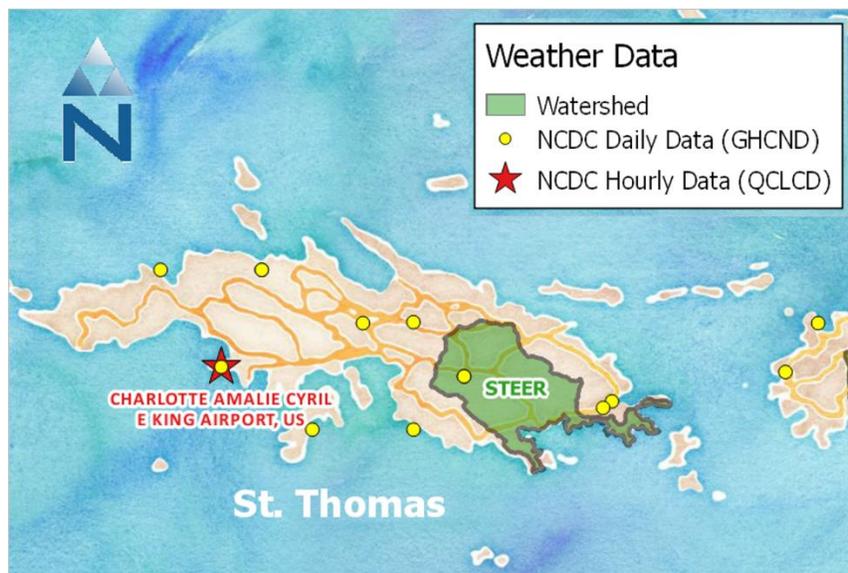


Figure 4-7. NCDC meteorological gaging stations on St. Thomas, USVI.

4.3.1.1 Quality Control

The Virgin Islands watershed model runs at an hourly time step. Previous experience has shown that the NCDC daily precipitation dataset tends to be more reliable, in terms of total reported volumes, than the hourly dataset; however, hourly gages are still incorporated into the process for rainfall disaggregation. Many of the rainfall stations contain intervals of missing, deleted, or accumulated data. Missing or deleted intervals are periods during which either the gage malfunctioned, or the data records were lost. Accumulated intervals contain cumulative precipitation reported over several hours or days, but the exact temporal distribution of the data is unknown due to a gage malfunction.

Two commonly used estimation techniques for patching missing rainfall data are the Normal Ratio Method (Dunne and Leopold, 1978) and the Distance Power Method. The Normal Ratio Method corrects for orographic variability through normalization; however, the Distance Power Method does not consider that. A hybrid approach was used for quality-controlling the Virgin Islands dataset. First, candidate stations were selected from among the gages using nearest distance to gage (a minimum of 3 nearby stations). The search radius was incrementally widened to add stations until at least one good candidate station from the same island was available for each impaired month in the historical record for the station. Stations were preferentially selected, but not weighted, by distance. Second, the Normal Ratio Method was used patch each station with its respective set of nearby stations. Patching of missing and deleted data intervals was performed on a daily time step basis. Next, those patched daily intervals were disaggregated to hourly using hourly rainfall distributions at nearby gages. The Normal Ratio Method estimates missing daily rainfall using a weighted average from surrounding stations with similar rainfall patterns according to the relationship:

$$P_A = \frac{1}{n} \left(\sum_{i=1}^n \frac{N_A}{N_i} \times P_i \right)$$

where P_A is the missing precipitation value at station A , n is the number of surrounding stations with valid data for the same day, N_A is the long-term average monthly precipitation at station A , N_i is the long-term average monthly precipitation at nearby station i , and P_i is the observed daily precipitation at nearby station i . For months where data were either zero or heavily impaired (i.e. more than 50% missing), the long-term average *annual* precipitation value was used for N_A and N_i instead of the impaired monthly values. For each missing day at station A , n consists of only the surrounding stations with valid data; therefore, for each day, n can vary from 1 to the maximum number of surrounding stations. When no precipitation is available at the surrounding stations from the same island, zero precipitation is also assumed at station A . In general, gages located at airports and relatively high population/traffic locations tend to have better data quality than those located in more remote locations.

Some of the gages contained long time intervals with no rainfall and no missing flags. Sometimes rainfall occurred at nearby stations during the un-flagged missing intervals. Some intervals were as short as one month, while others extended beyond a year. The longer the period of time, the less likely that there would truly be no rainfall occurring during that interval. For this reason, the original record was further adjusted to flag all “dry” intervals greater than 30 days as “missing,” thereby giving them the opportunity to be patched using nearby gages as applicable. Table 4-9 summarizes the final set of 30 rainfall gages from among the three islands considered for modeling. Quality control summaries for each gage are presented in Appendix E. The stations are sorted from highest quality to lowest quality. Attribute information includes elevation, rainfall evaluation period, percent missing (reported and adjusted), and average annual rainfall (reported and adjusted).

Table 4-9. Summary of Virgin Islands NCDC rainfall data compiled and processed for modeling

Quality Rank	Station Name	Station ID	Elevation (ft)	Evaluation Period ¹		Percent Missing ²		Rainfall (inches/year)	
				First	Last	Reported	Adjusted	Reported	Adjusted
1	CHRISTIANSTED AP	671624	61	1/2/1980	12/31/2020	0%	2%	36.23	36.94
2	EAST HILL	672560	120	1/5/1980	12/31/2020	0%	7%	38.47	41.12
3	MONTPELLIER	674900	200	2/2/1980	12/31/2020	0%	8%	33.75	36.67
4	CHARLOTTE AMALIE CYRIL	671640	20	3/24/1980	12/31/2020	0%	11%	36.17	39.53
5	BETH UPPER NEW WORKS	670480	110	1/2/1980	12/31/2020	3%	15%	23.80	27.75
6	WINTBERG	679450	645	9/3/1980	12/31/2020	14%	16%	35.71	42.11
7	EAST END	672551	150	1/6/1980	12/31/2020	0%	17%	31.48	36.52
8	CORAL BAY	671790	30	3/4/1981	9/30/2011	0%	18%	27.21	32.71
9	CRUZ BAY	671980	8	1/5/1980	12/31/2020	13%	18%	38.66	46.47
10	REDHOOK BAY ST THOMAS	677600	4	3/3/1980	12/31/2020	0%	24%	18.54	23.36
11	CHRISTIANSTED FORT	671740	30	1/3/1980	12/31/2020	0%	29%	26.19	36.55
12	ESTATE THE SIGHT	672870	130	2/3/1980	6/28/2002	35%	38%	22.16	37.01
13	GRANARD	673677	65	1/5/1980	6/19/2003	38%	38%	23.62	38.34
14	COTTON VALLEY 2	671810	140	2/2/1982	7/31/2001	44%	47%	14.97	28.96
15	ANNALY	670240	700	1/2/1980	2/21/2003	36%	47%	25.61	47.95
16	CANEEL BAY PLANTATION	671316	60	2/3/1980	2/19/1998	50%	53%	20.28	42.35
17	CATHERINEBURG	671348	845	1/5/1980	10/27/1996	54%	57%	19.42	43.28
18	ESTATE FORT MYLNER	672823	200	1/3/1980	8/30/1995	57%	61%	20.89	51.88
19	FOUNTAIN	673150	250	1/2/1980	4/29/1992	67%	67%	15.05	45.30
20	HAM BLUFF LIGHTHOUSE	673880	80	1/23/1980	10/29/1992	65%	68%	8.50	25.57
21	DOROTHEA AES	672440	800	1/4/1980	5/14/1993	64%	68%	13.51	38.50
22	LAMESHUR BAY	674820	170	1/10/1980	3/29/1989	76%	78%	8.46	36.26
23	WATER ISLE	679222	100	1/9/1980	7/25/1990	72%	79%	8.15	38.27
24	FREDERIKSTED 1 SE	673220	80	1/2/1980	8/30/1989	75%	87%	5.72	41.75
25	ESTATE HOPE	672830	390	5/7/1984	8/30/1989	85%	87%	6.70	50.80
26	PROSPECT HILL	676000	214	9/11/2012	12/31/2020	91%	92%	4.57	54.48
27	ESTATE RUST-OP-TWIST	672860	50	3/22/1980	7/29/1984	91%	92%	3.72	41.90
28	BORDEAUX MOUNTAIN	670820	1,110	1/6/1980	7/30/1984	89%	93%	3.14	42.73
29	CHARLOTTE AMALIE 2	671625	15	1/9/1980	11/21/1981	97%	97%	1.51	43.04
30	TAGUE BAY	678621	30	1/7/1980	5/28/1981	98%	99%	0.70	42.24

1. Evaluation period (for data processing): 1/1/1980 – 12/31/2015. Actual start and end date ranges of the gages may extend outside this window.
2. Percent missing: “Reported” are flagged missing intervals in the dataset over the evaluation period. “Adjusted” includes un-flagged dry intervals longer than 30 days.

Figure 4-8 presents a 25-year summary of annual precipitation totals at Charlotte Amalie Airport (671640) for the period October 1, 1990, through September 30, 2015. The thinner line (dark blue) shows measured precipitation, the thicker line (orange) shows the processed or “patched” precipitation record, and the bar graph (blue-gray) shows percent missing per year. The original dataset had an un-flagged dry interval between 5/9/1996 and 8/6/1998, longer than 2 years. Figure 4-9 shows that Christiansted Airport (671624), which had the best quality data, had a 33-day un-flagged dry interval in 2005 between 4/8 and 5/11. Patching rainfall from nearby gages added about 5 inches of rainfall during that interval, raising the annual total from about 33 inches to 38 inches.

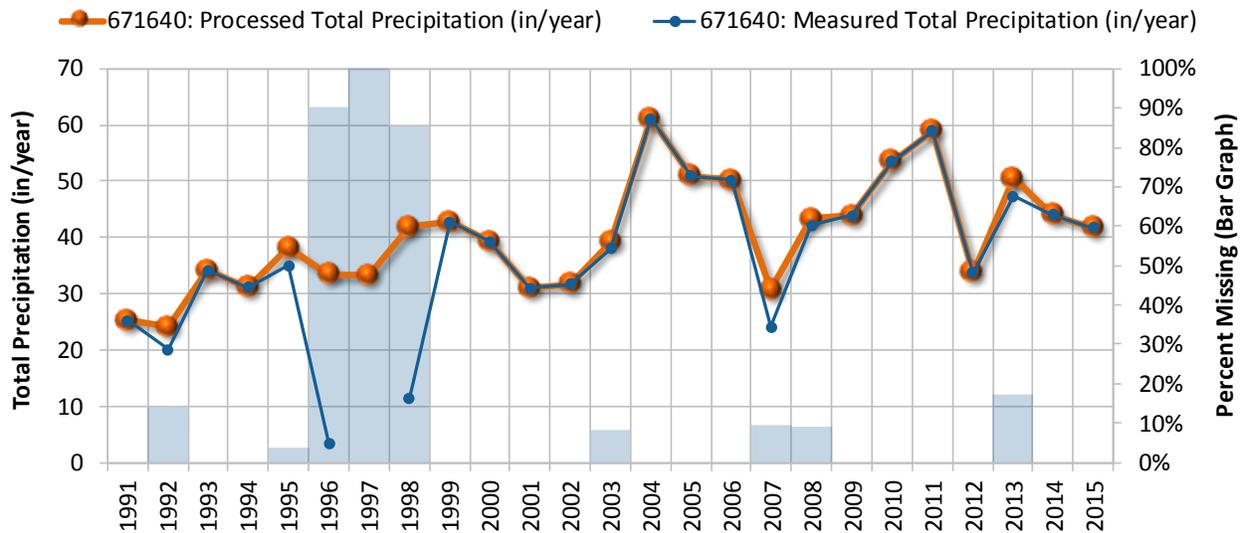


Figure 4-8. Total Precipitation at CHARLOTTE AMALIE CYRIL (671640), 1991-2015.

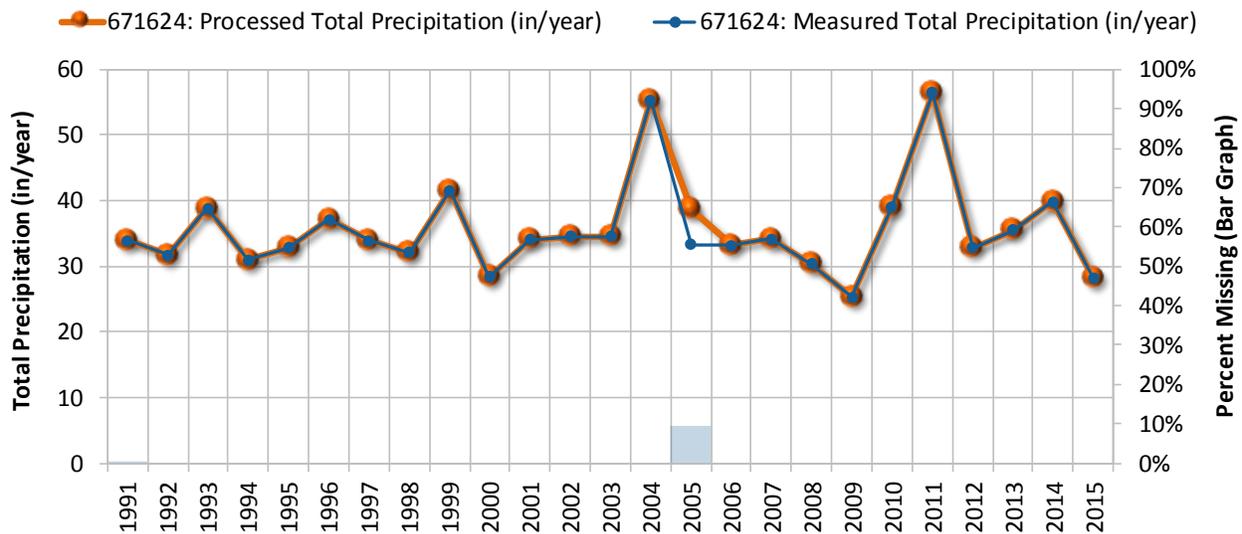


Figure 4-9. Total Precipitation at CHRISTIANSTED AP (671624), 1991-2015.

Figure 4-10 summarizes patching results from all stations. Annual average rainfall totals confirm just how variable rainfall can be at different locations among the three islands. The top 10 highest quality

stations are specifically called out in the graph. Those were used for long-term simulation runs for the TMDL; however, during calibration, some of the other gages were selectively assigned for certain periods of time because in some instances (for specific storms), where they had good data, the storms were more representative of localized rainfall in those watersheds. Total estimated rainfall was also plotted against gage elevation to check for any discernable trends. In general, the lowest elevation gages reported the lowest rainfall totals; the totals also somewhat increased with elevation. However, the irregularity in that trend corroborates the belief that other factors like aspect, terrain-induced rain shadow, and island-to-island rainfall variability also influences long-term average rainfall totals.

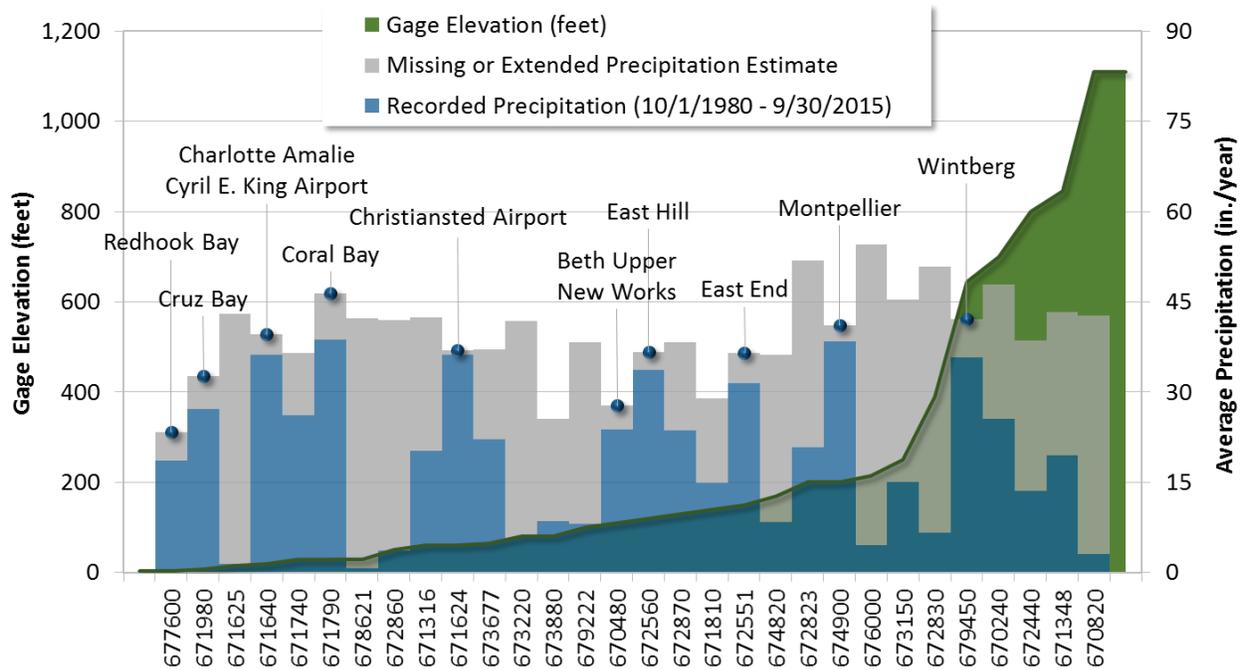


Figure 4-10. Regional NCDC rainfall totals vs. gage elevation.

4.3.2 Potential Evapotranspiration

Evaporation and evapotranspiration (ET) account for a large portion of the hydrologic water budget in most places. Simplified methods such as the Hamon and Jensen approaches are often applied because it is convenient to estimate ET as a function of fewer meteorological constituents. Because of the relatively narrow seasonal variability in climate conditions, those methods are often as robust as the more rigorous energy-balance based approaches. The Pathogen Study used the Hamon method with default coefficient values to derive ET for SUSTAIN (Cadmus, 2011). For this effort, ET was also computed using the default Hamon method, which estimates ET as a function of temperature. Daily ET is disaggregated to hourly over daylight hours as a function of latitude.

Potential ET varies as a function of vegetative cover. ET coefficients were applied as a function of land cover to reflect stratification of vegetative impacts, as summarized in Table 4-10. This approach provides more spatial resolution by allowing it to vary as a function of land use, which varies by subwatershed. Two gages among the islands had the best quality long-term temperature timeseries for computing ET: (1) Charlotte Amalie Cyril E. King Airport on St. Thomas, and (2) Christiansted Hamilton Field Airport on St. Croix. The Cyril E. King Airport was used for the northern islands of St. Thomas and St. John, while Hamilton Field Airport was used for St. Croix. Although each island is assigned one timeseries as the basis for ET, land-cover-specific stratification (Table 4-10) adds spatial variability as a function of vegetative cover.

Table 4-10. Estimated stratification of modeled ET by land cover type

Cover Type	Land Cover	Evapotranspiration Multiplier	Rationale ¹
Urban	Impervious	1.2	Above average ET (warm exposed surfaces)
	Pervious	0.9	Grass or shrub vegetation
	Construction	1.0	No vegetation, use standard ET rate
Rural	Agriculture	0.9	Grass or shrub vegetation
	Barren	0.9	Grass or shrub vegetation
	Forest/Wetland	0.85	Light wind, high relative humidity
	Grass-Shrub	0.9	Grass or shrub vegetation
Water	Water	1.0	Use evaporation rate for open water

1. Reference: Bedient and Huber, 2002. Table 1.2, Page 47.

4.4 Data Gaps

4.4.1 Hydrological Data Gaps

Aside from the meteorological data gaps described in Section 4.3.1, there were very few USVI flow gages with high-quality long-term continuous flow monitoring. For the reported gage data, there was also a relatively high frequency of “estimated” flags among the USGS flow data, suggesting that the ephemeral-to-intermittent flow conditions in the stream channels (commonly referred to as “guts”) have been challenging to measure accurately. In fact, USGS flow monitoring in USVI ended altogether in 2006 due to government budget shortfalls. Table 4-11 summarizes the quantity and quality of USGS data in USVI.

The USGS *StreamStats* application was used to develop flow statistics for the selected calibration sites to evaluate model performance during the more recent period from 2006 through 2020 when observed, continuous data was not available.

4.4.2 Water Quality Data Gaps

There were no instream monitoring stations within the guts of any of the watersheds. All of the gages were in the estuarine portions of listed TMDL waterbodies. This data gap was addressed by setting water quality parameter values in the watershed model based on literature values shown in Table 4-7.

Table 4-11. Quantity and quality of USGS streamflow records by water year (Source Data: USGS)

Data Quantity (**Blue**: Percent Complete) and Data Quality (**Red**: Percent Estimated)

Legend (% Complete/Estimated): ○ 0% ◐ 10%-20% ◑ 30%-60% ◒ 70%-90% ● 100%

USGS Station ID	Water Years (October 1, 1985 – September 30, 2003)																	
	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
50274000					●	●	●	●	●	●	●	●	●	●	●	●	●	●
					◑	○	○	○	◐	○	◐	◑	◒	●	◐	◐	○	◐
50292600					●	●												
					○	○												
50294000				◐	●	●												
				○	○	◐												
50295000	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	○	○	○	○	○	○	○	◐	◐	○	◐	○	◐	◐	◑	◐	◐	◑
50295500				◐	●													
				○	○													
50332000				●	●													
				○	○													
50333500			●	●	●	◐												
			○	○	○	○												
50334500			●	●	●	●	●	◐										
			○	○	○	○	○	○										
50337500				◐	◐													
				○	○													
50345000	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	◐	◐	◐
	◐	○	○	○	○	○	◐	◐	◑	◐	◐	◑	◐	◐	○	○	○	○
50348000				◐	◐													
				○	○													
50349000				●	◐													
				○	○													

4.5 Time Frame of Simulation

The model simulation and climate inputs cover the period from October 1, 1980 through September 30, 2020. Calibration was conducted from 10/1/1992 through 9/30/2006 to coincide with the most recent continuous streamflow data. Additional validation was performed using available streamflow gages statistics for a more recent period from 10/1/2011 through 9/30/2020.

5 MODEL CALIBRATION

Calibration refers to the configuration and refinement of the analytical instruments that are used to generate analytical data. As alluded to in the Quality Assurance Project Plan (QAPP) document for this project, by analogy the “instrument” is the predictive tool (i.e., the model) that is to be developed and/or applied. The goal is to link delineated characteristics associated with model segmentation with observed conditions the water bodies of interest. Figure 5-1 is a schematic describing a process for model calibration that aims to minimize the propagation of uncertainty. This process builds upon the model development cycle and elements of data quality control previously described in Section 2.1.

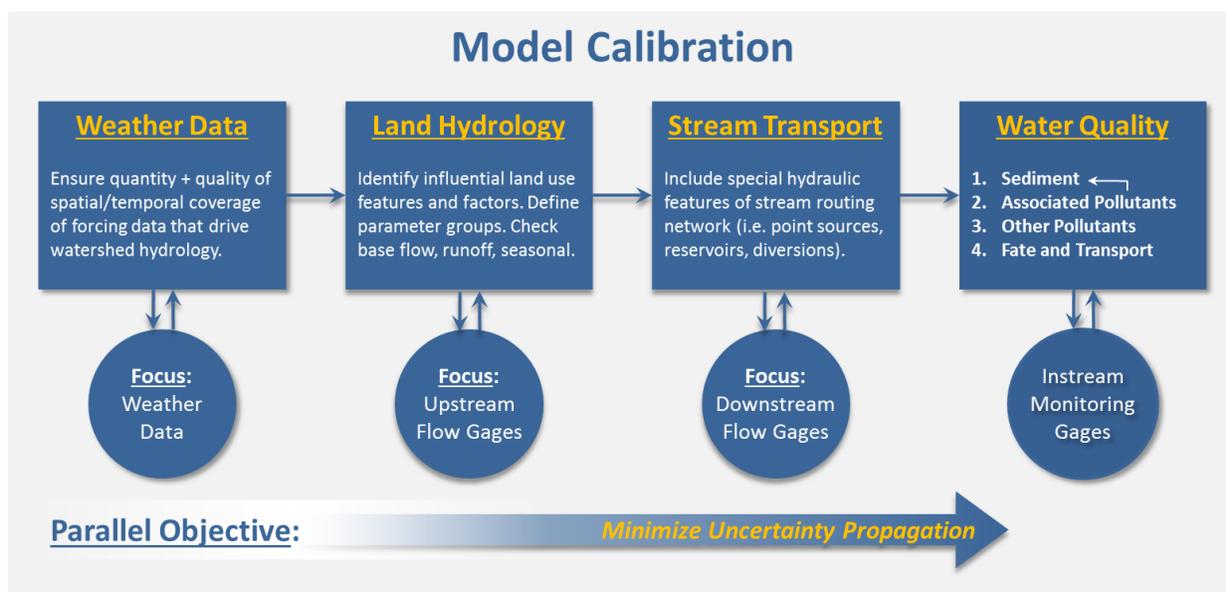


Figure 5-1. Process for model calibration to minimize propagation of uncertainty.

This study builds upon the efforts and lessons learned from previous modeling studies in the region. As described by Cadmus (2011):

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).

The model calibration process aims to establish causal relationships between meteorological conditions, delineated model components, and predicted hydrology and water quality responses, in comparison to observed conditions. For this reason, using data for time intervals at locations with the best observed data quality minimizes the chance of propagating error associated with data uncertainty. In keeping with a top-down weight-of-evidence-based methodology, model calibration focused on specific time intervals at locations with overlapping periods of high rainfall and streamflow data quality. At each location, parameters associated with the predominant drainage area HRU characteristics (i.e., land use, slope, or soil group) were the focus of calibration.

Table 5-1 summarizes upstream drainage area HRU characteristics for each of the USGS gages presented in Table 4-11. In general, smaller upstream gages, which were predominantly high-sloped forested watersheds, were first used to calibrate the relative magnitude and duration of background flow conditions. The larger downstream watersheds (which exhibited mixed land use, soils, and slope characteristics) were then used to adjust other HRU parameters.

Table 5-1. Upstream drainage area HRU characteristic for each USGS gage

USGS Station ID	Model Drainage Area (acres)	Land Use				Slope		Hydrologic Soil Group			
		Forest Wetland	Grass Shrub	Agriculture Barren	Developed	High (≥15%)	Low (< 15%)	A/B	C	D	Mixed
50274000	1,490	46%	20%	1%	33%	36%	64%	3%	0%	62%	35%
50292600	249	99%	0%	0%	1%	90%	10%	0%	91%	6%	2%
50294000	947	93%	1%	0%	6%	56%	44%	2%	2%	89%	7%
50295000	240	81%	3%	1%	16%	60%	40%	0%	0%	84%	16%
50295500	118	75%	5%	0%	20%	56%	44%	0%	0%	79%	21%
50332000	922	52%	26%	3%	18%	34%	66%	48%	4%	27%	20%
50333500	2,526	36%	21%	20%	23%	11%	89%	4%	16%	36%	44%
50334500	2,666	31%	28%	20%	20%	16%	84%	15%	25%	19%	41%
50337500	137	66%	34%	0%	0%	73%	27%	0%	0%	99%	1%
50345000	1,372	68%	26%	2%	4%	50%	50%	0%	3%	92%	6%
50348000	231	56%	36%	0%	8%	64%	36%	0%	65%	27%	8%
50349000	59	15%	76%	0%	9%	80%	20%	0%	82%	9%	9%

5.1 Water Balance Calibration

Calibration of the modeled water balance primarily involved the first two elements in Figure 5-1 (Weather Data and Land Hydrology). Key model components influencing hydrology, hydraulics, and the overall water balance that were evaluated as part of model configuration included: (1) precipitation data quantity and quality, (2) evaporation and evapotranspiration rates. Rainfall in USVI is often localized—two nearby gages can often report notably different rainfall totals for the same storm event. When results did not match observed trends, wind data and historical hurricane logs were referenced to qualify the direction and movement of storms.

Rainfall gages were initially assigned to modeled subwatersheds using the Thiessen polygon method. This approach is typically applied to stations that are several miles apart and cover a wide watershed area; however, because an entire island is sometimes 6 to 15 miles from one side to another, any gage

on the island could be considered as representative depending on the movement of specific storms. Because the islands are small and storms can be variable and localized, the default station assigned using the Thiessen polygon method did not always represent the storms for all time periods as well as different gage. For this reason, different gages on each island were tried at each calibration point to see which one was the most representative of most storms. Performance varied from storm to storm—some were better reflected at certain gages than at others. For each calibration watershed, the rainfall gage on each island that captured most of the storms was ultimately selected as the gage to be used for model calibration.

The top-down weight of evidence approach was implemented in the following sequence (1) calibrate background conditions, (2) add intermediate mixed land use areas, and (3) aggregate all sources via routing to a downstream location for comparison with co-located flow data. Figure 5-2 is a schematic showing the parameterization and calibration sequence for land hydrology.

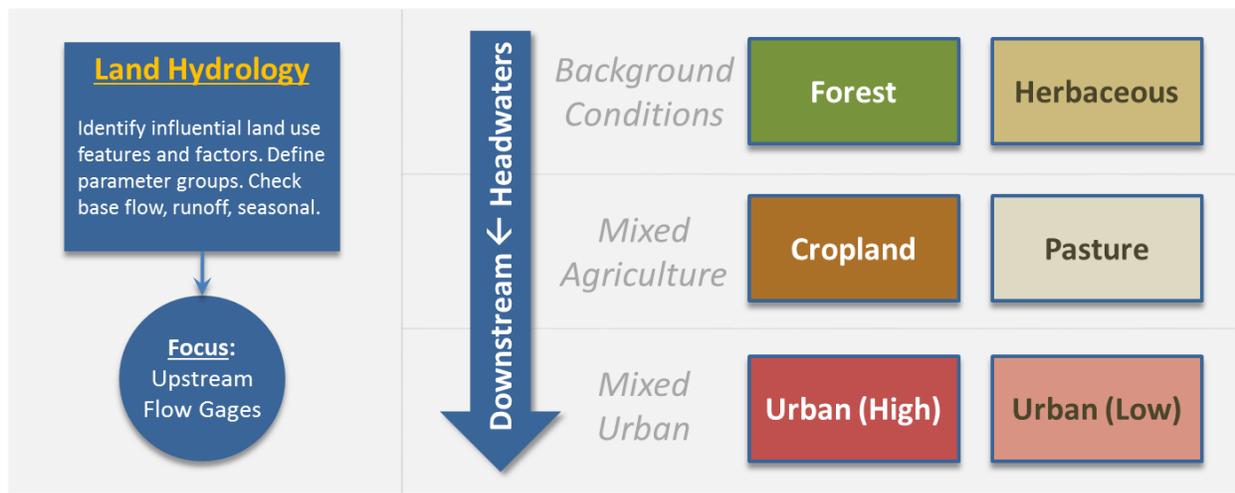


Figure 5-2. Model parameterization and calibration sequence for land hydrology.

For hydrologic calibration of HSPF, a variety of performance targets have been specified, including Lumb et al. (1994) and Donigian (2000). As previously noted, the LSPC model is functionally identical to USEPA’s HSPF model in terms of hydrologic and water quality processes. Based on those literature sources, performance targets for simulation of the water balance components are summarized in Table 5-2. The general acceptance criterion for models to be applied in this project is to achieve a quality of fit of “Good” or better.

Table 5-2. Typical performance targets for LSPC hydrology simulation (modeled vs. observed)

Model Component	Very Good	Good	Fair	Poor
Error in Total Volume	< 5%	5-10%	10-15%	> 15%
Error in 10% Highest Flow Volumes	< 10%	10-15%	15-25%	> 25%

Calibration outcomes are explained, with some insights and rationale provided for both “Very Good” to “Poor” calibration metrics in light of the top-down weight-of-evidence approach described above. The variety of graphical and statistical points of comparison include:

- Time series plots of modeled versus observed streamflow (Section 6.1 and Section 6.2)
- Numerical calibration metrics vs. performance targets (Section 6.1, Section 6.2, and Section 6.3)

5.2 Model Parameters

Using the approach outlined in the previous section, the final calibrated parameters for LSPC watershed model are presented in Table 5-3.

Table 5-3. Summary of calibrated hydrology parameters

Parameter	Description	Unit	Value
LZSN	Lower Zone Nominal Soil Moisture Storage	inches	0-0.7
INFILT	Index to Infiltration Capacity	in/hr	0-0.2
KVARY	Variable groundwater recession	1/inches	0-3.0
AGWRC	Base groundwater recession	none	0-0.87
CEPSC	Interception storage capacity	inches	0.05-0.15
UZSN	Upper zone nominal soil moisture storage	inches	0-1.1
NSUR	Manning’s n (roughness) for overland flow	none	0.05-0.3
INTFW	Interflow inflow parameter	none	0
IRC	Interflow recession parameter	none	0-0.8
LZETP	Lower zone ET parameter	none	0-0.7
PETMAX	Temp below which ET is reduced	deg. F	45
PETMIN	Temp below which ET is set to zero	deg. F	35
INFEXP	Exponent in infiltration equation	none	2
INFILD	Ratio of max/mean infiltration capacities	none	2
DEEPFR	Fraction of GW inflow to deep recharge	none	0-0.1
BASETP	Fraction of remaining ET from baseflow	none	0-0.1
AGWETP	Fraction of remaining ET from active GW	none	0-0.7

5.3 Water Quality Calibration

Other factors, besides pollutant loading, influence how a waterbody responds to loadings from various pollutant sources. As previously described, the mixing model methodology uses a mixing ratio as a basis for normalizing the influence of these competing factors. The mixing ratio measures how daily watershed flow volumes of background ocean water mix flow and loads from contributing sources. Geometric analysis of each assessment unit was performed to provide a physical basis for selected mixing ratios.

Bathymetric data for each assessment unit were used to calculate (1) average depth, (2) the ratio of bottom depth at the opening to average depth (which indicates efficiency of lateral mixing between the waterbody and open waters) and (3) the ratio of waterbody opening to shoreline perimeter (which indicates how narrow or wide the opening of the waterbody is for mixing). For each of these indicators, the higher the value, the more conducive it is for improving mixing efficiency. For illustrative purposes, a relative symbolic scale was developed for each of the three indicators to illustrate the impact of that indicator on mixing efficiency. Table 5-4 presents a legend of numeric ranges corresponding to the symbols show Table 5-5, which summarizes those geometric properties for each assessment unit.

For each waterbody, the mixing ratio was adjusted and calibrated so that diluted model concentrations resembled observed concentrations. The dilution volume was validated for each waterbody relative to others in reference to physical attributes such as width/narrowness of the estuary opening, bathymetric obstructions, orientation of the estuary opening relative to upwelling and wind-driven storm movement, and the location of monitoring gages within the estuary. Critical-condition concentrations were calculated for each pollutant for each representative day per month. The limiting month for each pollutant was the month with the highest modeled pollutant concentration. This result was also used to validate the model.

Table 5-4. Legend for geometric properties table

Legend of Geometric Properties (See Table 5-5)				
Entry, Interpretation		Average Depth	Lateral Mixing	Opening Width
●	<i>High</i>	Over 10 m	No bottom obstruction	Over 45%
◐	<i>Medium</i>	3 - 10 m	Some obstruction	25 - 45%
○	<i>Low</i>	3 m or less	Obstructed	25% or less

Table 5-5. Summary of measured geometric properties and calibrated critical mixing ratio and volume for each Assessment Unit

Watershed	Waterbody ID	Waterbody Name	Mixing Ratio*	Dilution Volume		Geometric Properties			
				m ³	% of Total	Average Depth	Lateral Mixing	Opening Width	Opening Direction
St. Thomas East End Reserve (STEER)	STT-25	Great Bay	50.0	29,297	0.2%	●	●	◐	N/E
	STT-28	Cowpet Bay	7.0	3,960	0.5%	◐	●	◐	S
	STT-31	Nazareth Bay	8.0	4,526	0.2%	◐	●	◐	S
	STT-33	Benner Bay	10.0	8,085	0.3%	◐	●	◐	S
	STT-34	Benner Bay Lagoon Marina	8.0	4,526	9.83%	○	○	○	S
	STT-35	Mangrove Lagoon	2.5	9,486	1.9%	○	○	○	S

Symbol Legend: ● High, ◐ Medium, ○ Low (See Table 5-4 for corresponding numeric ranges for each symbol)

* Mixing Ratio: Number of average daily watershed flow volumes used for dilution.

6 MODEL EVALUATION AND ACCEPTANCE

Model evaluation focused on confirming the model’s ability to represent systematic long-term behavior seen in the observed data. This process focused on time periods with overlapping intervals of both high-quality observed precipitation and flow. Due to the limitations in data available across the USVI, gages on islands other than St. Thomas were needed to demonstrate model performance.

6.1 Calibration Example: Jolly Hill Gut, St. Croix

At Jolly Hill Gut, daily-intersected rainfall and flow intervals were summarized over a 10-year period (10/1/1996 – 9/30/2006). Table 6-1 summarizes modeled vs. observed results during intervals represented by the four combinations of good and estimated rainfall vs. flow data quality. Model calibration focused on intervals with both “good” observed rainfall and “good” observed flow, as represented by the red-outlined boxes in Table 6-1, which represented 68 percent of both observed flow days and observed flow volume. Figure 6-1 is a monthly summary of modeled vs. observed flow and data quality. The top hyetograph also includes percent missing rainfall (gray), which was estimated from nearby gages using the Normal Ratio Method. The bottom flow time series graph shows both percent estimated (light blue) and percent missing (gray) for observed flow as reported by USGS at the gage. On the basis of this review, a two-year continuous period (10/1/1997 – 9/27/1999) was selected as the most representative calibration time period at Jolly Hill Gut. It included a dry year and a wet year (including the remnants of Tropical Storm Nicole, Nov-Dec 1998). It also represented the longest stretch of continuous “good” observed rainfall and “good” observed flow data. Figure 6-2 through Figure 6-5 show daily, monthly, seasonal average, and seasonal interquartile comparisons of modeled versus observed hydrology for the selected calibration period.

Table 6-1. Model performance at Jolly Hill Gut for good-and-estimated rainfall vs. flow data quality intervals

Rainfall Data Quality	Percent of Days		Percent of Flows		Percent Difference	
	Flow Data Quality		Flow Data Quality		Flow Data Quality	
	Observed	Modeled	Observed	Modeled	Observed	Modeled
Observed	68%	23%	68%	24%	7%	17%
Modeled	5%	4%	5%	3%	-45%	35%

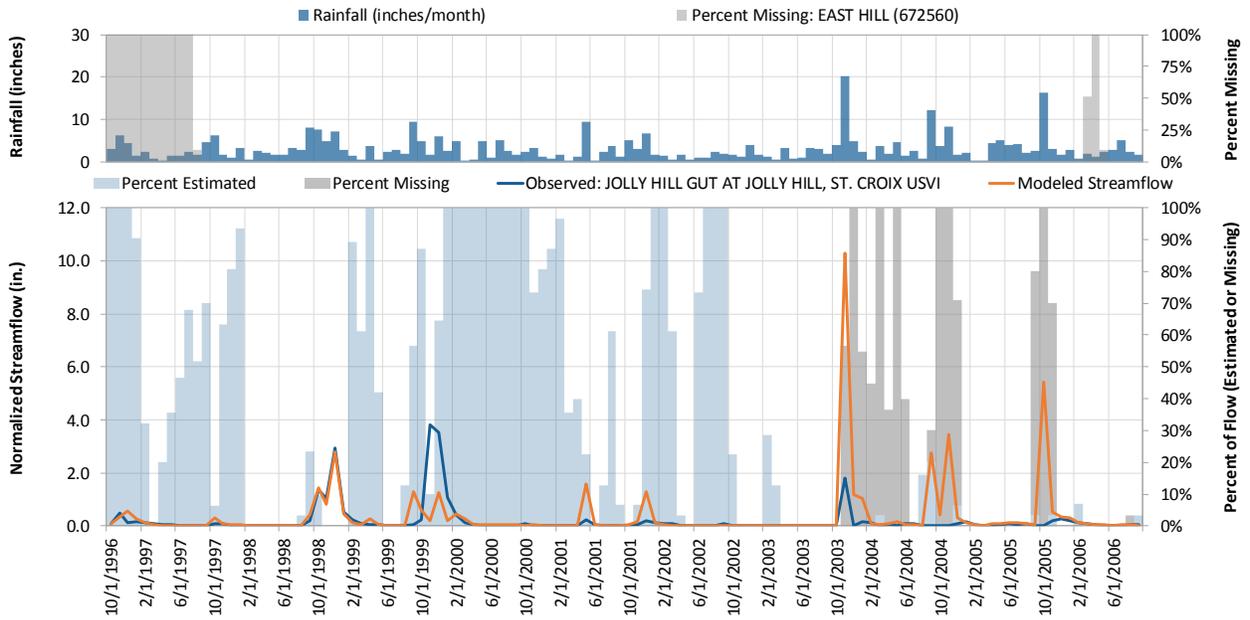


Figure 6-1. Temporal data quality summary for model calibration at JOLLY HILL GUT AT JOLLY HILL, ST. CROIX USVI (Station ID: 50345000).

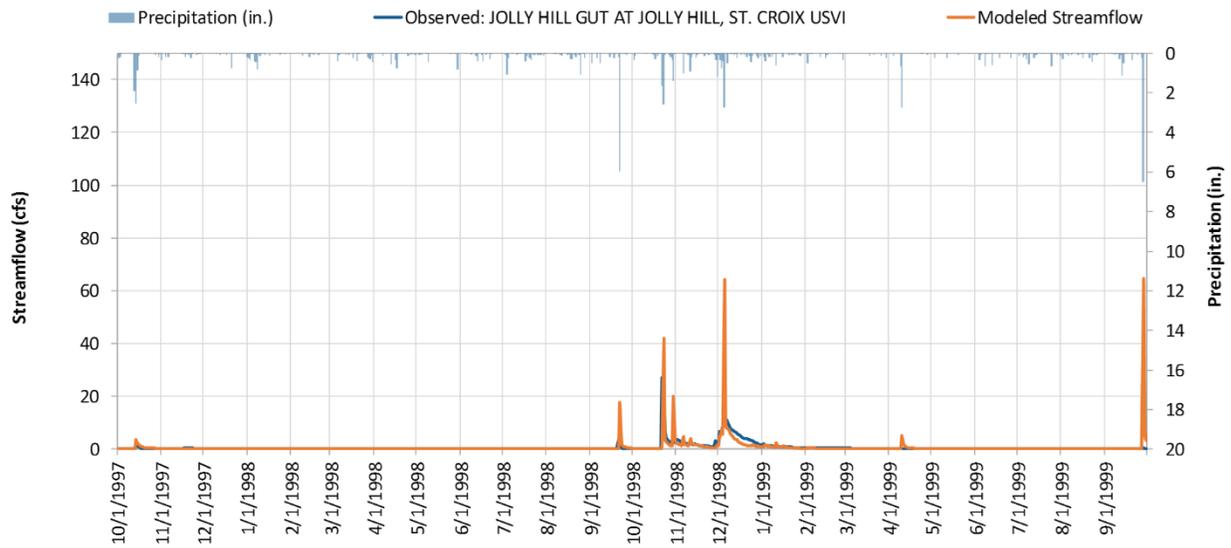


Figure 6-2. Daily modeled versus observed streamflow at JOLLY HILL GUT AT JOLLY HILL, ST. CROIX USVI (Station ID: 50345000).

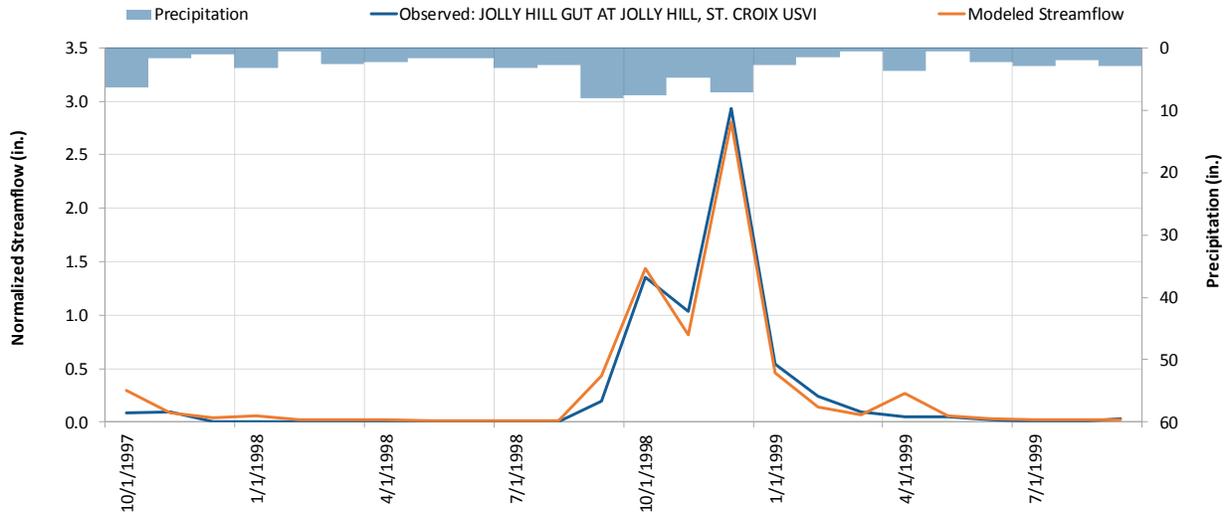


Figure 6-3. Monthly modeled versus observed streamflow at JOLLY HILL GUT AT JOLLY HILL, ST. CROIX USVI (Station ID: 50345000).

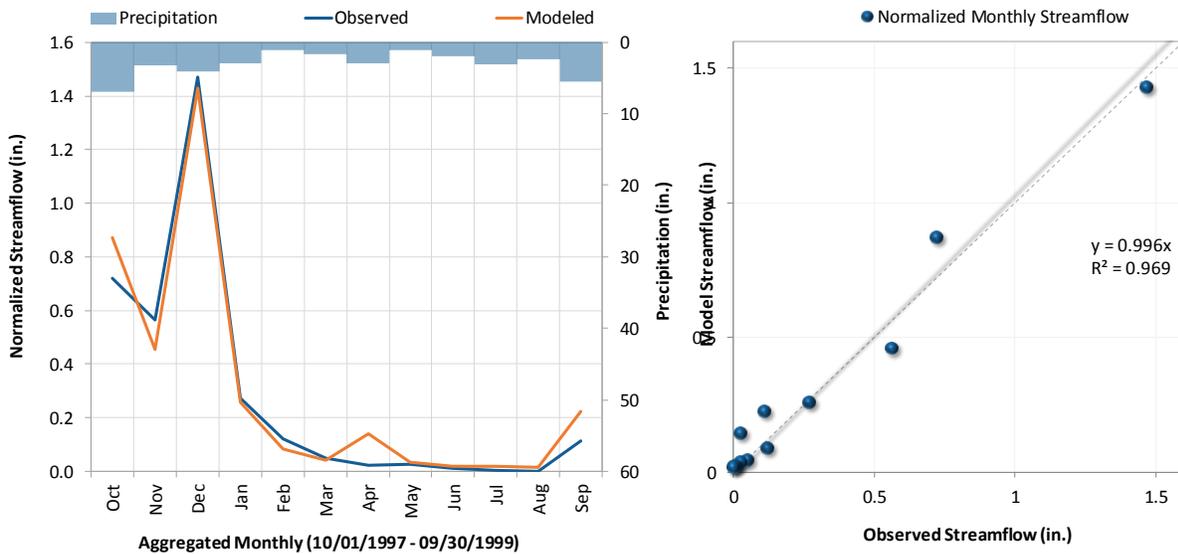


Figure 6-4. Seasonal average modeled versus observed streamflow at JOLLY HILL GUT AT JOLLY HILL, ST. CROIX USVI (Station ID: 50345000).

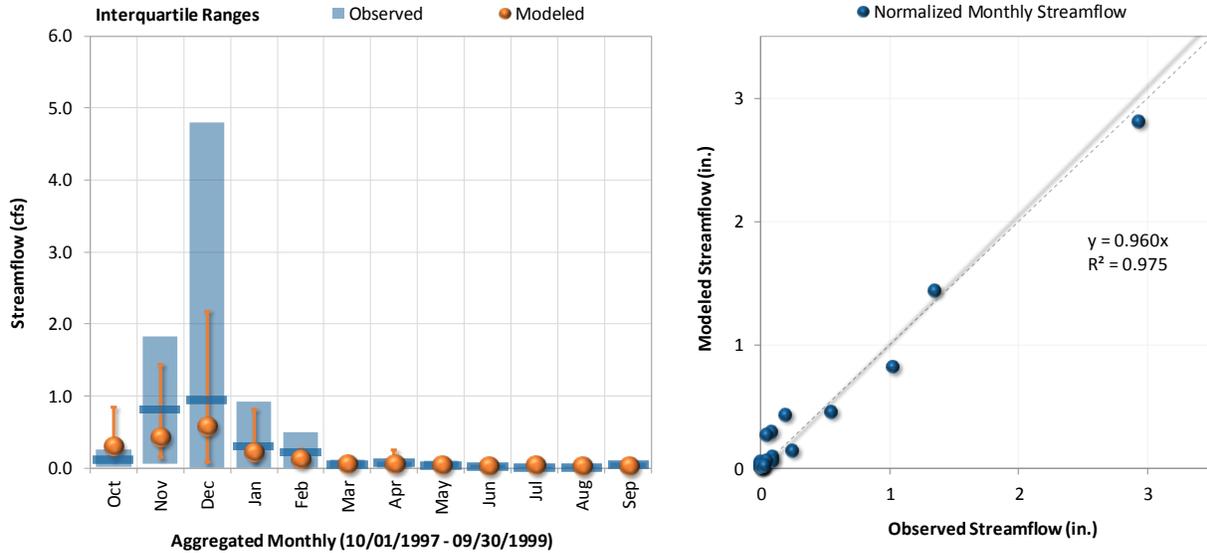


Figure 6-5. Seasonal interquartile modeled versus observed streamflow at JOLLY HILL GUT AT JOLLY HILL, ST. CROIX USVI (Station ID: 50345000).

6.2 Calibration Example: Turpentine Run, St. Thomas

At Turpentine Run, daily-intersected rainfall and flow intervals were summarized over a 14-year period (10/1/1992 – 9/30/2006). Model calibration focused on time periods with overlapping intervals of both high-quality observed precipitation and flow. Table 6-2 summarizes modeled vs. observed results during intervals represented by the four combinations of good and estimated rainfall vs. flow data quality. Model calibration focused on intervals with both “good” observed rainfall and “good” observed flow, as represented by the red-outlined boxes in Table 6-2, which represented more than 50 percent of both observed flow days and observed flow volume.

Within the observed flow record, there was an anomalous 2-day event (9/15-9/16/1995), which neither appeared in the rainfall record as impaired for flow nor rainfall. There was also no reported tropical storm for those days. When those two days were removed from the observed flow record, the percent difference between modeled and observed flow improved from -19 percent to +7 percent. Figure 6-6 is a monthly summary of modeled vs. observed flow and data quality (the anomalous observed flow value is also shown in the graph). Figure 6-7 through Figure 6-10 show daily, monthly, seasonal average, and seasonal interquartile comparisons of modeled versus observed hydrology for the selected calibration period.

Table 6-2. Model performance for Turpentine Run at Mt. Zion, St. Thomas, for good-and-estimated rainfall vs. flow data quality intervals

Evaluation Period	Rainfall Data Quality	Percent of Days		Percent of Flows		Percent Difference	
		Flow Data Quality		Flow Data Quality		Flow Data Quality	
		Observed	Modeled	Observed	Estimated	Observed	Estimated
All Days	Observed	53%	26%	61%	26%	-19%	-46%
	Modeled	18%	3%	11%	1%	-65%	-82%
Excluding 9/15 and 9/16/1995	Observed	53%	26%	54%	32%	7%	-46%
	Modeled	18%	3%	11%	2%	-54%	-82%

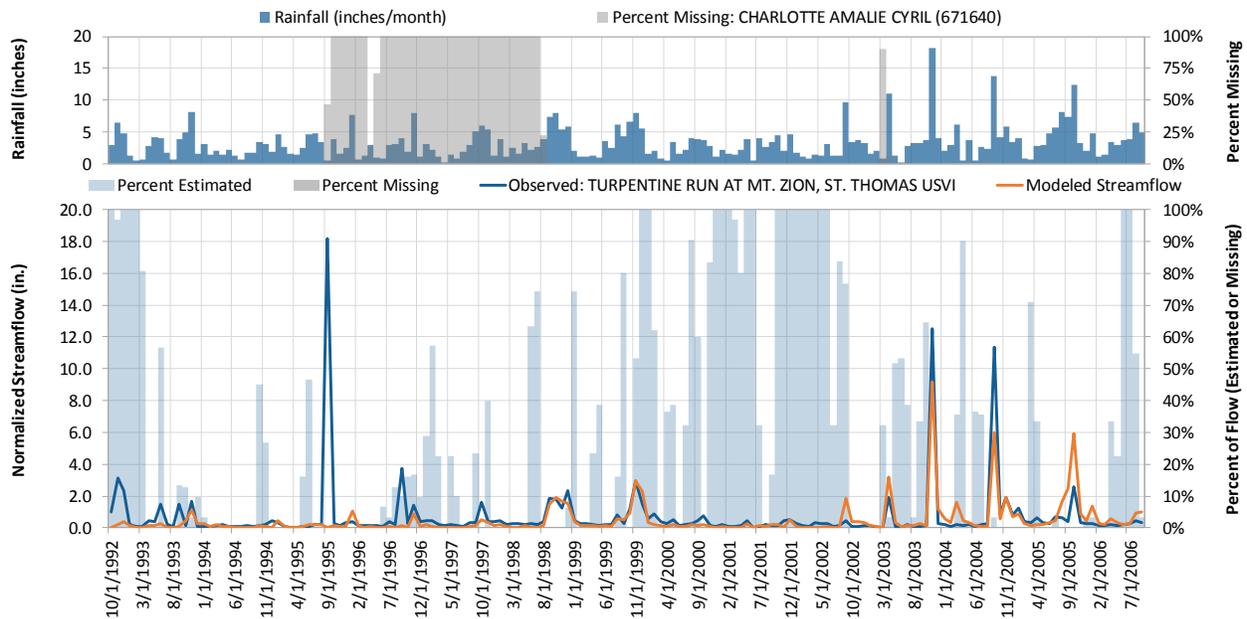


Figure 6-6. Temporal data quality summary for model calibration at TURPENTINE RUN AT MT. ZION, ST. THOMAS USVI (Station ID: 50274000).

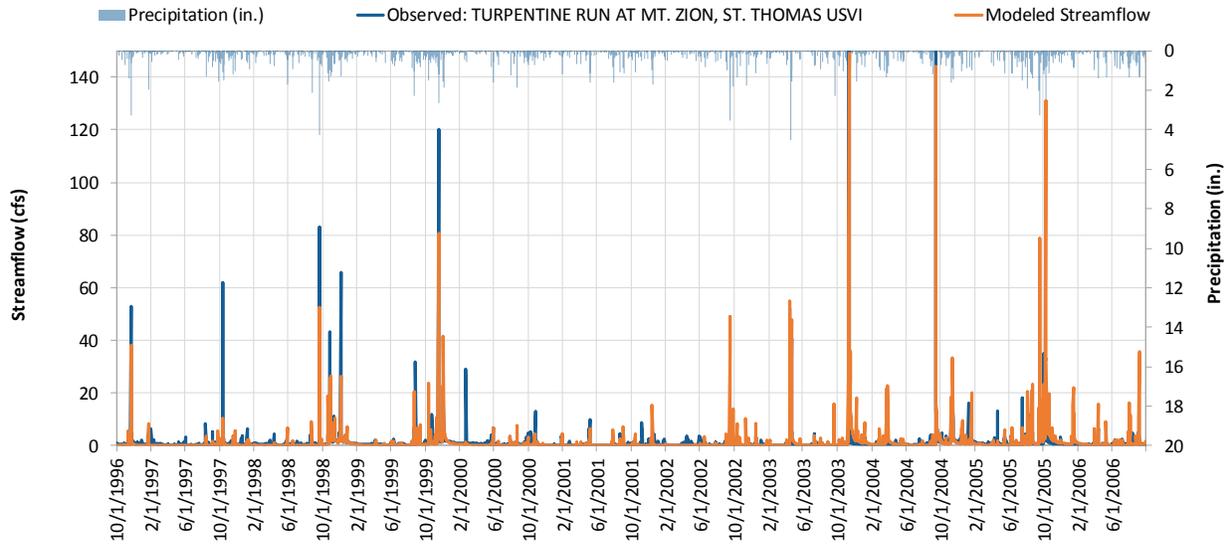


Figure 6-7. Daily modeled versus observed streamflow at TURPENTINE RUN AT MT. ZION, ST. THOMAS USVI (Station ID: 50274000).

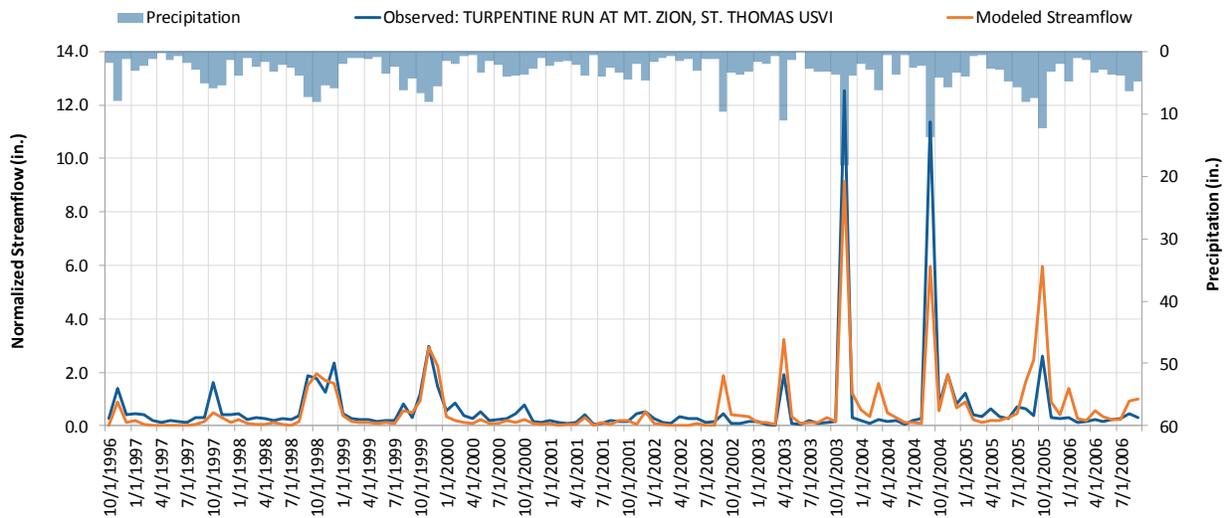


Figure 6-8. Monthly modeled versus observed streamflow at TURPENTINE RUN AT MT. ZION, ST. THOMAS USVI (Station ID: 50274000).

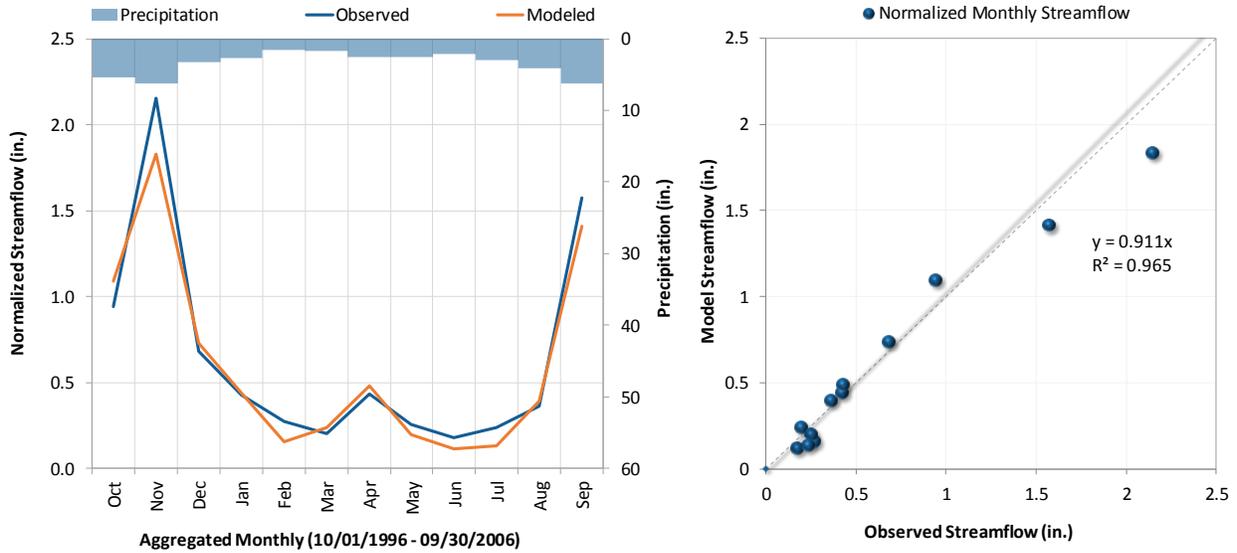


Figure 6-9. Seasonal average modeled versus observed streamflow at TURPENTINE RUN AT MT. ZION, ST. THOMAS USVI (Station ID: 50274000).

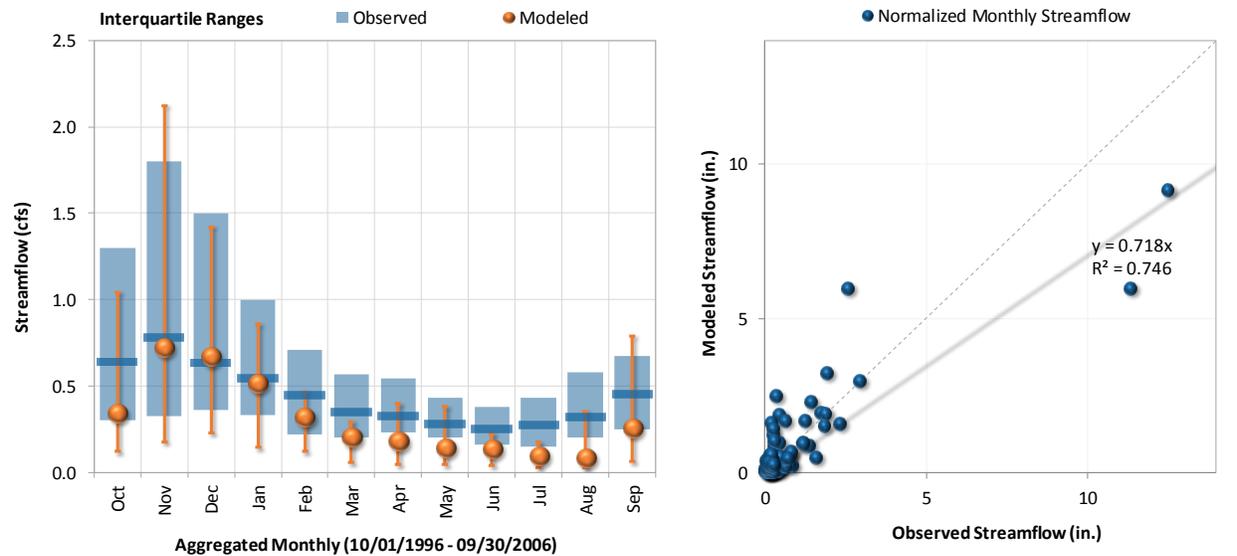


Figure 6-10. Seasonal interquartile modeled versus observed streamflow at TURPENTINE RUN AT MT. ZION, ST. THOMAS USVI (Station ID: 50274000).

6.3 Validation Example: Turpentine Run, St. Thomas

An independent validation period from October 1, 2011 through September 30, 2020 was evaluated for the Turpentine Run at Mt. Zion, St. Thomas streamflow gage comparing mean and 95th percentile statistics from the model to comparable values derived using the USGS *StreamStats* application (USGS, 2021). The mean annual flow statistic was chosen to evaluate the overall water balance represented in the model while the 95th percentile statistics was chosen to specially evaluate wet weather when non-point source runoff and pollutant loading is highest. Table 6-3 presents a comparison of the mean annual and 95th percentile flow between *StreamStats* and the LSPC watershed model for the Turpentine

Run at Mt. Zion, St. Thomas gage. Generally, the model predictions align with the expected statistics and meet the criteria for calibration presented in Table 5-2.

Table 6-3. Comparison of the mean annual and 95th percentile flow between StreamStats and model for Turpentine Run at Mt. Zion, St. Thomas

Evaluation Period	Metric	Mean Annual Flow		95 th Percentile Flow	
		StreamStats	Modeled	StreamStats	Modeled
10/1/2011 – 9/30/2020	Flow (cfs)	2.9	2.5	3.9	3.5
	% Error	--	-13.8%	--	-10.3%

6.4 Water Quality Model

Observed data consistently showed that November has the highest bacteria concentrations in most of the water bodies. November also corresponds with the beginning of the season when the live-aboard population increases in USVI. Table 6-4 presents the critical condition month with the highest concentration for each modeled pollutant.

Table 6-4. Critical condition month for each TMDL waterbody and pollutant under existing conditions

Watershed	Waterbody ID	Waterbody Name	Critical-Condition Month				
			TSS	BOD5	TN	TP	ENTERO
St. Thomas East End Reserve (STEER)	VI-STT-34	Benner Bay Lagoon Marina	10	1	2	2	10
	VI-STT-35	Mangrove Lagoon	8	7	7	7	9
	VI-STT-25	Great Bay	10	7	10	10	10
	VI-STT-28	Cowpet Bay	10	3	3	3	10
	VI-STT-31	Nazareth Bay	10	3	2	3	10
	VI-STT-33	Benner Bay	10	11	10	10	11

Due to the lack of instream water quality monitoring (all gages were in estuarine portions of the listed TMDL waterbodies), stratifying loads across contributing sources in a representative manner was an important modeling objective. First, event-mean concentrations (EMC) for each pollutant were stratified and assigned to each HRU in the model. Second, modeled runoff and pollutant loads were summarized by land use and validated against unit-area loading rates from literature. In the absence of instream monitored water quality from the watershed, the EMC assignments with comparison of locally estimated unit-area loads formed the basis for representing watershed-originated pollutant loads for this study. Some literature estimates were derived from local TMDLs and watershed management plans, but some others were referenced from other studies. Figure 6-11 shows modeled versus literature values for unit-area sediment loading by land use, slope, and hydrologic soil group among all modeled USVI subwatersheds. The blue quartile box and whiskers represent the range of annual unit-area loads from all modeled subwatersheds, while the red boxes outline the range of unit-area loads (minimum to maximum) from among the reviewed literature. Table 4-7 previously summarized the range of unit-area loads from the respective data sources for each pollutant and land use type—the red boxes in the box plots represent the range of these literature values. Modeled vs. literature values for the other pollutants BOD5 (Figure 6-12), ENTERO bacteria (Figure 6-13), TN (Figure 6-14), and TP (Figure 6-15), are subsequently presented.

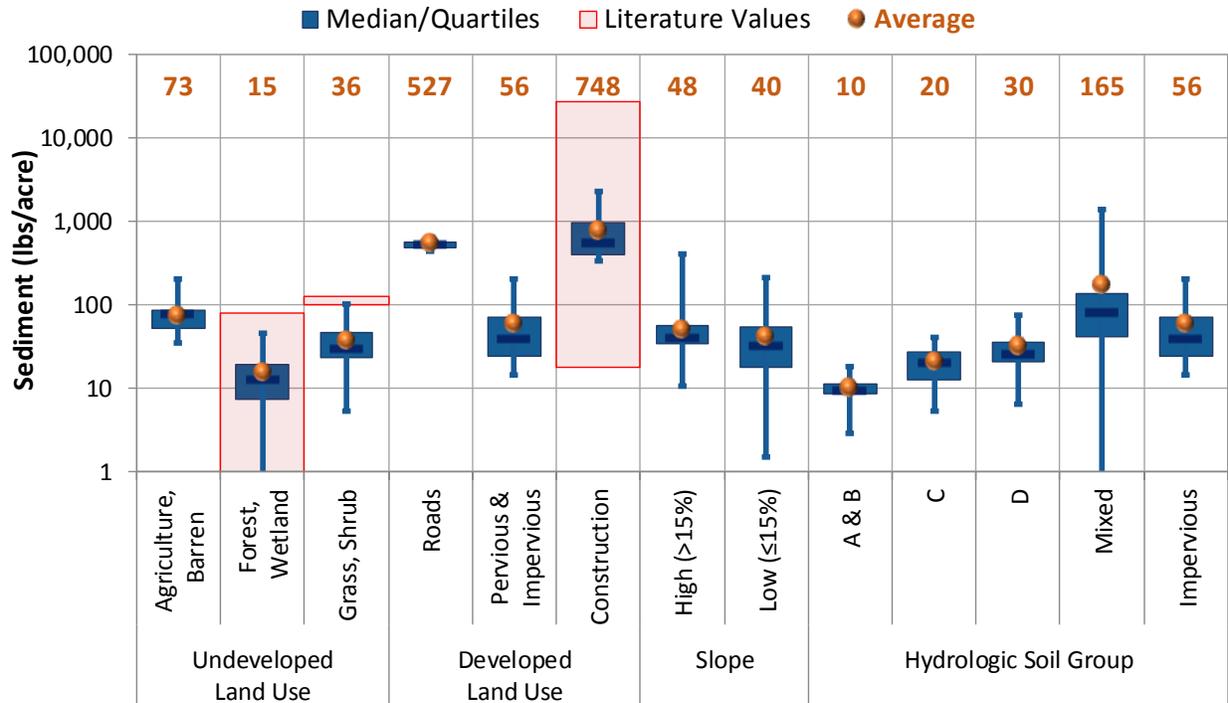


Figure 6-11. Modeled unit-area sediment (lbs/acre) for all watersheds.

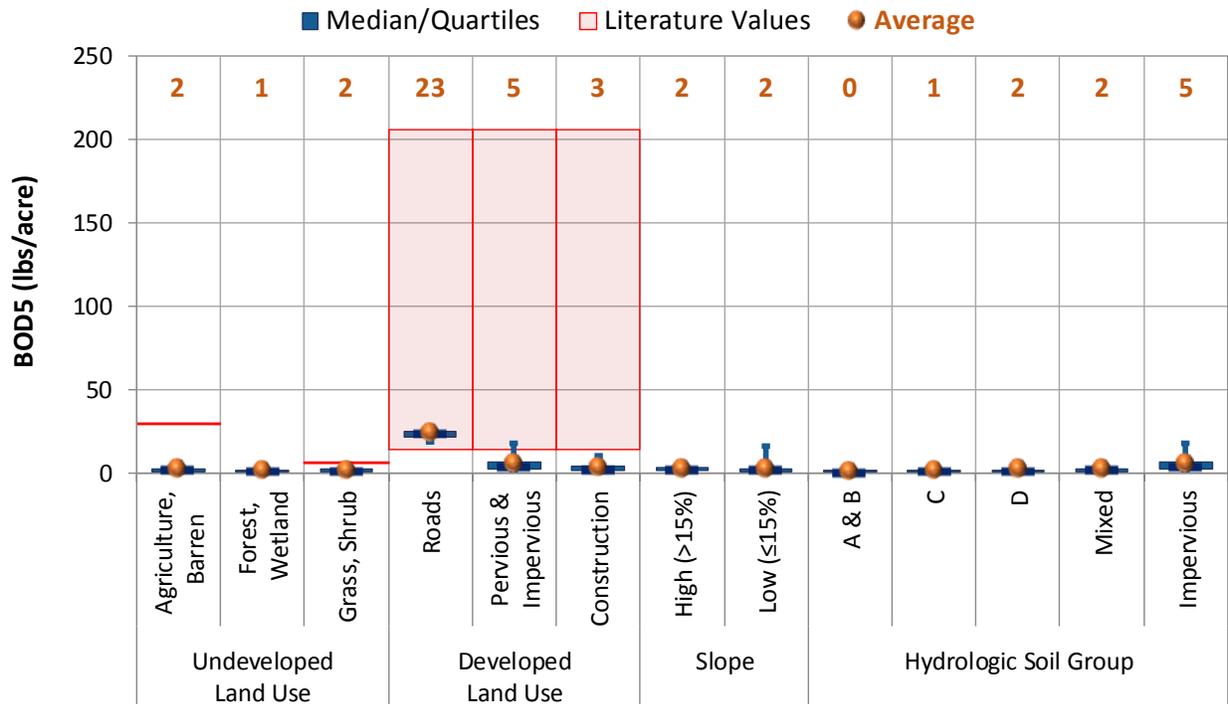


Figure 6-12. Modeled unit-area BOD5 (lbs/acre) for all watersheds.

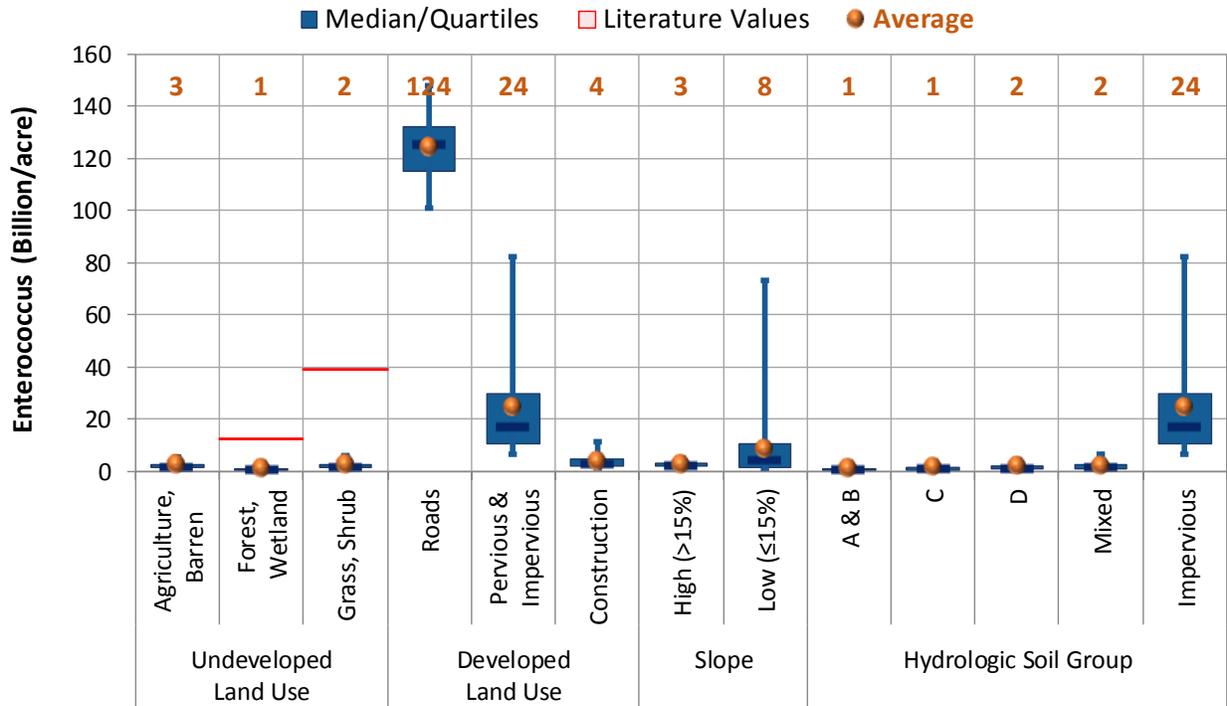


Figure 6-13. Modeled unit-area ENTERO (Billion/acre) for all watersheds.

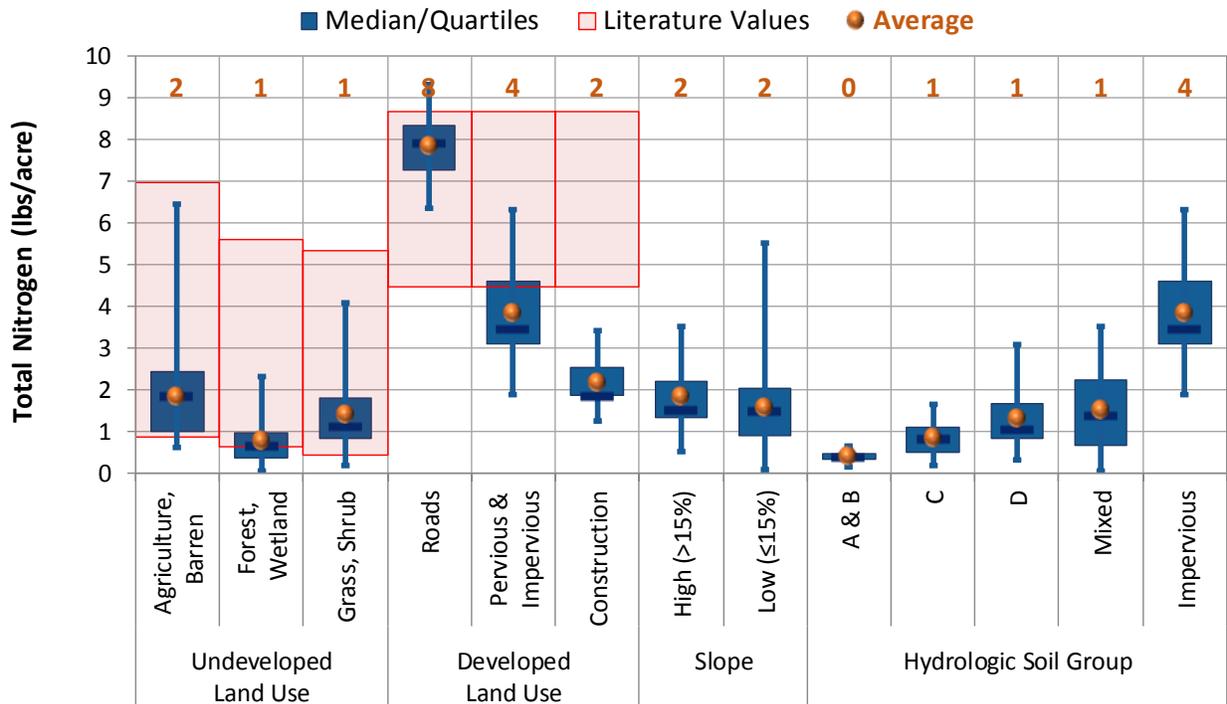


Figure 6-14. Modeled unit-area TN (lbs/acre) for all watersheds.

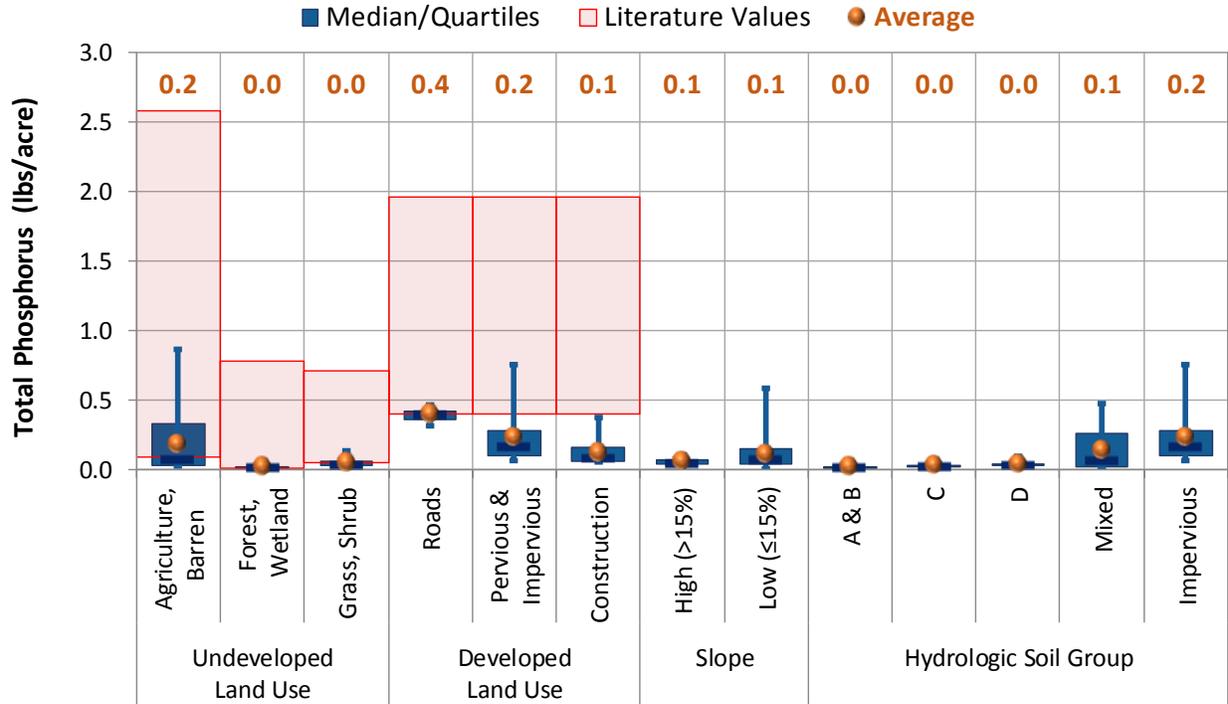


Figure 6-15. Modeled unit-area TP (lbs/acre) for all watersheds.

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