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INTERDEPENDENT INFRASTRUCTURE RESILIENCE IN THE U.S. VIRGIN ISLANDS: PRELIMINARY ASSESSMENT

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14. ABSTRACT

The U.S. Virgin Islands (USVI) is a territory comprised of three main islands—Saint Croix, Saint John, and Saint Thomas—and a number of smaller surrounding islands, located in the Leeward Islands of the Lesser Antilles approximately 40 miles east of Puerto Rico and over 1,100 miles from Miami, Florida. In September 2017, two Category-5 hurricanes made landfall within a two-week period and collectively devastated the homes, businesses, and infrastructure throughout the Territory. This technical report (1) explains the structure, function, and tensions associated with energy, water, transportation, and communication infrastructure that were chronic problems prior to the hurricanes; (2) documents hurricane response, recovery, and mitigation activities for these infrastructure systems after the hurricanes; and (3) provides concrete approaches to overcome potential barriers to resilience (where they exist) and open questions for research (where they do not yet exist).

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ABSTRACT

The U.S. Virgin Islands (USVI) is a territory comprised of three main islands—Saint Croix, Saint John, and Saint Thomas—and a number of smaller surrounding islands, located in the Leeward Islands of the Lesser Antilles approximately 40 miles east of Puerto Rico and over 1,100 miles from Miami, Florida. In September 2017, two Category-5 hurricanes made landfall within a two-week period and collectively devastated the homes, businesses, and infrastructure throughout the Territory. This technical report (1) explains the structure, function, and tensions associated with energy, water, transportation, and communication infrastructure that were chronic problems prior to the hurricanes; (2) documents hurricane response, recovery, and mitigation activities for these infrastructure systems after the hurricanes; and (3) provides concrete approaches to overcome potential barriers to resilience (where they exist) and open questions for research (where they do not yet exist).

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List of Acronyms and Abbreviations

AMR	Automatic Metering Recording
BVI	British Virgin Islands
CID	Center for Infrastructure Defense
CNO	Chief of Naval Operations
CPB	Corporation for Public Broadcasting
DC	direct current
DHS	U.S. Department of Homeland Security
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EAG	Energy Academic Group
EDIN	Energy Development in Island Nations
EIA	U.S. Energy Information Administration
EMS	emergency management service
FEMA	Federal Emergency Management Agency
FCC	Federal Communications Commission
GVI	Government of the Virgin Islands
HRSG	Heat Recovery Steam Generators
HIT	Hurricane Infrastructure Team
HVAC	heating, ventilation and air conditioning
ILEC	incumbent local exchange carrier

IP Office of Infrastructure Protection

kWh kilowatt-hour

LED light-emitting diode

LFG Landfill Gas

LMR land-mobile radio

LPG liquefied propane gas

MGD million gallons per day

MW megawatt

NDRF National Disaster Recovery Framework

NIPP National Infrastructure Protection Plan

NPS Naval Postgraduate School

NREL National Renewable Energy Laboratory

OM operations and maintenance

OR Operations Research

PBS Public Broadcasting Service

PCCIP President's Commission on Critical Infrastructure Protection

PPD Presidential Policy Directive

PSA Protective Security Advisor

PV photovoltaic

REG renewable energy generation

RO reverse osmosis

RHGS Randolph Harley Generating Station

RSF	Recovery Support Functions
SCADA	Supervisory Control and Data Acquisition
SECNAV	Secretary of the Navy
STJ	Saint John
STT	Saint Thomas
STX	Saint Croix
TandD	transmission and distribution
USCG	United States Coast Guard
USVI	United States Virgin Islands
VIBIT	Virgin Islands Bureau of Information Technology
viNGN	Virgin Islands Next Generation Network
WAPA	Water and Power Authority
WWT	Waste Water Treatment

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Executive Summary

The U.S. Virgin Islands (USVI) Territory is comprised of three main islands—Saint Croix, Saint John, and Saint Thomas—and several smaller surrounding islands, located in the Leeward Islands of the Lesser Antilles approximately 40 miles east of Puerto Rico and over 1,100 miles from Miami, Florida. In September 2017, two Category-5 hurricanes made landfall within a two-week period and collectively devastated homes, businesses, and infrastructure throughout the Territory.

The significant damage across all infrastructure systems and services prompted efforts by the US Federal government, USVI Territorial government, and local communities to 'build back better' and make island infrastructure resilient to future disasters. However, building back better is no simple task, and requires significant effort to restore, redesign, and rethink all Territory infrastructure. For example, the USVI Hurricane Recovery and Resilience Task Force report commissioned by the Territorial Government (see www.usvihurricanetaskforce.org) recommends a total of 228 initiatives spread across a variety of sectors to improve critical infrastructure and public services and make businesses more resilient to future storms and other disasters. These initiatives include Climate Analysis (5), Energy (17), Private Sector Communications (14), Public Sector Communications (11): Transportation (24),Water (11), Solid Waste and Wastewater (26), Housing and Buildings (11), Health (21), Vulnerable Populations (12), Education (20), Economy (9), Non-profit, Philanthropy, and Voluntary Organizations (6), and Government Response (41). With so much to be done, it is hard to know how to prioritize efforts, particularly when personnel and resources are limited. Moreover, significant research and practical experience teach us that decisions that superficially appear to improve infrastructure resilience may only exacerbate problems. New vulnerabilities can arise when operational decisions are mismatched across infrastructure systems and organizations work at cross purposes.

The objective of this report is to provide Federal, Territorial, and local stakeholders a baseline for prioritizing efforts to build back better by presenting an operational view of 'how USVI lifeline infrastructures work' and offering recommendations to overcome possible barriers to critical infrastructure resilience. The four lifeline infrastructure systems studied in this report are (1) energy, with emphasis on electricity; (2) water; (3) transportation; and (4) telecommunications. Avoiding potential pitfalls for infrastructure resilience in these systems starts with two key recognitions. First, it is important to understand critical infrastructure not merely as a list of assets (e.g., facilities, cables, pipes, etc.), *but as a system of components that work together to deliver function*. Resilience is not gained by increasing the availability of individual assets per se, but by improving the capacity for systems to function and keep the lights on, water flowing, people mobile, and communications available. The second key recognition is that *the behavior of infrastructure systems is the result of active management*—often by a mix of humans and/or automated technologies—to meet overall service objectives. Service objectives are difficult to reconcile and may conflict, as short term response to disruptive events may prioritize efforts to 'minimize service outages,' yet longer term service objectives may be 'minimize cost' or 'maximize profit,' particularly for infrastructures that are owned by private entities. Reconciling the needs of different decision-making entities—which we refer to as *infrastructure operators*—helps identify ways to achieve resilience in lieu of limited equipment, personnel, or other resources. The starting point for assessing how USVI energy, water, transportation, and communication systems respond to disruptive events (and in turn, how to improve this response) is to take an *operational view* of the drivers and constraints on infrastructure function within each system. This operational view includes engineering, economic, and regulatory knowledge with enough detail to explain how infrastructure systems may realistically respond to changes in design and management.

This report presents an operational view of 'how USVI lifeline infrastructures work' to support prioritization efforts in the following ways:

1. This report explains the structure, function, and tensions associated with energy, water, transportation, and communication infrastructure that were chronic problems *prior to the hurricanes*. Each of these systems suffered from chronic challenges to their ongoing management prior to the hurricanes of 2017. Our analysis includes detailed descriptions of installed infrastructure, infrastructure condition, system structure, system function, management activities, markets, and long-term plans that influenced their operation leading up to the hurricanes.

2. This report documents hurricane response, recovery, and mitigation activities for these infrastructure systems after the hurricanes. Both the immediate response and longer-term recovery of lifeline infrastructure systems will have a profound effect on their resilience.

Our analysis documents ongoing activities to improve these critical infrastructure systems in 2018. Our analysis is neither comprehensive nor authoritative, particularly because what constitutes 'ground truth' is rapidly evolving. Instead, this report contributes to the continued shared awareness among various stakeholders and supports discussions regarding current efforts to enhance resilience.

3. This report discusses these changes in the context of potential barriers to resilience. We frame past and current infrastructure operations within the context of four common barriers to resilience and offer ways to overcome them. By providing an operational view, we can identify how current and planned resilience activities address potential barriers. We provide concrete approaches to overcome barriers (where they exist) and open questions for research (where they do not yet exist).

Overall, common issues that preclude resilience stem from functional limitations of existing infrastructure systems and long-standing economic issues inhibiting operations, maintenance, and management practices. Functional issues include the centralized and fragile structure of electricity and potable water systems alongside geographic, geologic, and regulatory requirements that limit the capacity of water drainage systems and roadway management. Economic limitations exacerbate these issues, as all lifeline systems lack effective ways to ensure long-term funding and solvency in normal operations and during disasters. Electricity and potable water systems are particularly vulnerable to long-term economic issues as decentralized power and water generation on each island creates competition among local utilities and the private sector. Current policies and practices for distributed power generation and clean water use may undermine the infrastructure quality and upgrades in the future.

With respect to chronic and acute infrastructure challenges, this report identifies ways to inform future resilient systems across the USVI Territory. Specifically, collaborative efforts conducted across the Naval Postgraduate School, U.S. Department of Energy, National Renewable Energy Laboratory, and Sandia National Laboratories will support future island resilience. One example is new analysis on the interdependent operation of electric power and water distribution systems, both of which are owned and operated by the USVI Water and Power Authority. The new analysis will develop interdependent infrastructure models that embed technical information about the demands and locations for both systems and measure the capacity for past and future infrastructure to get power and water from supply to demand. The new models support analysis about future disasters that amount to a systematic analysis of 'what-if' scenarios involving the loss of one or more infrastructure components and measuring how interdependent systems and operators may respond to these disruptions. These models also support investments in hardening, redundancy, or new infrastructure construction to help mitigate potential service interruptions and contribute to the shared vision of a resilient Territory.

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1 Introduction

The United States Virgin Islands (USVI) is a territory comprised of three main islands—Saint Croix (STX), Saint John (STJ), and Saint Thomas (STT), see Figure 1—and a number of smaller surrounding islands, located in the Leeward Islands of the Lesser Antilles approximately 40 miles east of Puerto Rico and over 1100 miles from Miami, Florida.

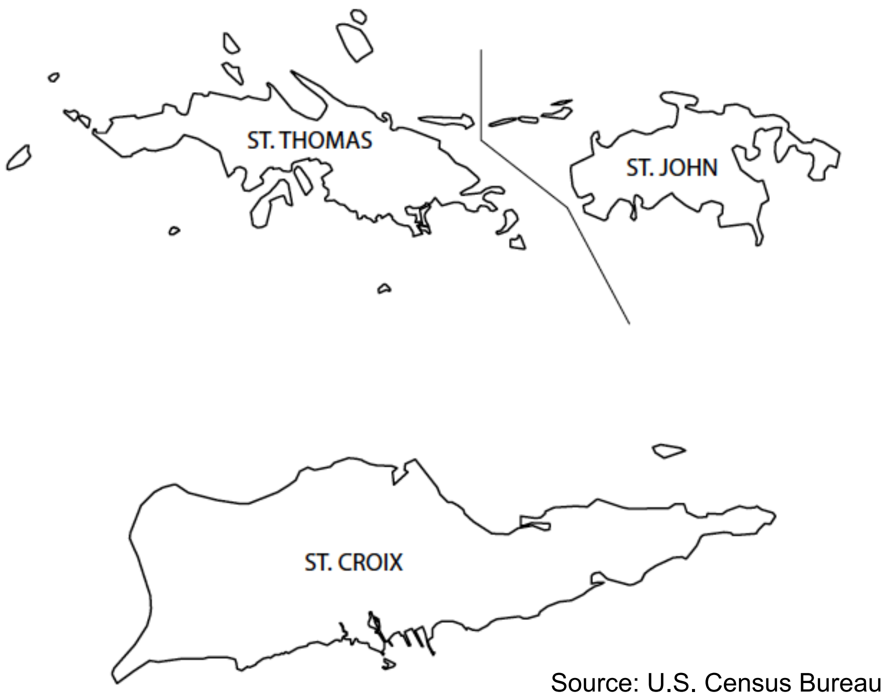

Figure 1. The three main islands of the U.S. Virgin Islands (not to scale).

As of the 2010 U.S. Census, the population of the entire territory was approximately 106,000 (Appendix A.1 provides a summary of basic demographic information about the island territory). However, it is important to note the distinct characteristics of each island (USVI Department of Public Works 2014):

> "Historically, each island has developed differently according to its geography. St. Thomas has traditionally been, and continues to be a commercial port due to the deep water harbor of Charlotte Amalie. St. Thomas is also one of the most popular cruise ship destinations in the Caribbean. St. Croix at one time thrived as a plantation island producing sugar, but has since developed light industry

> due to its abundance of flat land. Attempts to develop a tourist economy on par with St. Thomas on the island of St. Croix continue to be a primary goal of the Virgin Islands government. St. John started as a plantation island, but the Danish government abandoned the island economically after the slave revolt in 1733. As such, much of the island was undeveloped when the Virgin Islands National Park was created in 1956. As a result of the park, privately owned property is a valuable resource on St. John, providing sites for luxury residences."

The USVI is a territory with limited natural resources and modest local agricultural and manufacturing sectors; this requires the islands to import most of its food, finished goods, and energy. The remoteness of the USVI territory makes its imports expensive. Foremost among these are its energy imports. Historically, the Virgin Islands Water and Power Authority (WAPA), the utility provider for the territory, burned imported fuel oil (and more recently liquid propane) to produce its electricity. In 2017, electricity rates in the USVI were approximately three times higher than the average rate in the 50 U.S. States (U.S. Energy Information Administration 2017). These costs are vulnerable to global energy market volatility, creating a significant source of financial risk to WAPA and its customers. Further exacerbating matters, the USVI median household income and per capita income are significantly lower than the mainland U.S., by approximately 26% and 22%, respectively, according to a 2018 Congressional Research Service report (Clark et al. 2018). The high relative cost for energy makes everything else more expensive, which ultimately means that businesses and residents alike have relatively fewer financial resources to invest in things beyond the operation of daily life.

Historically, the economy of the USVI has been heavily dependent on tourism, rum production, and oil refining, with some additional manufacturing primarily on STX (U.S. Virgin Islands Bureau of Economic Research 2014). However, the global recession of 2008-2009 and the closing of the Hovensa refinery in 2012 caused significant economic losses across the Territory. Hovensa employed nearly 1,200 residents and approximately 2,500 contractors, and its operations sustained a large, indirect collection of businesses supporting refinery operations. Financially, the closing of Hovensa resulted in an estimated decline of $140 million in annual tax revenue (Clark et al. 2018). According to the 2015 Comprehensive Economic Development Strategy (U.S. Virgin Islands Bureau of Economic Research 2014), economic revenues across the Territory declined by 65% during 2007-2012 and in 2013 unemployment had risen to 11%-15% on the islands, nearly twice the average of 7.4% in the mainland U.S. This economic slowdown for individuals and businesses has also created a financial crisis for the government in the form of lost tax revenues. The most recent data from FY2016 and FY2017 show the Government of the Virgin Islands (GVI) had a budget deficit of $110 million, debt totaling $2 billion, and $3.4 billion in unfunded pension liability and debt to WAPA (Clark et al. 2018).

These financial troubles in the USVI are not new. The USVI public sector has been burdened with budgetary problems that compromised the maintenance and reliability of the Territory's infrastructure systems for many years (U.S. Department of Energy 1982). For example, the GVI is the largest customer of WAPA and is historically slow to pay its electricity bills. Public reports show GVI owing WAPA $41.2 million in unpaid water and electricity bills for 2018 (Knight 2018). The inconsistent cash flow from the government to WAPA is one of the challenges facing the utility's electric grid operations and maintenance (O&M) program which in turn causes grid reliability to suffer. Due to relatively high costs and sometimes unreliable power, many of WAPA's largest electricity customers have disconnected from the public grid, which further decreases revenues for WAPA and creates an increased financial burden for remaining customers.

Because of the prominent role that energy plays in the economic and social welfare of the Territory, there have been concerted efforts in the USVI over the last decade to develop energy efficiency and renewable energy projects as a means to combat problems with both cost and reliability. In particular, the Energy Development in Island Nations (EDIN) pilot project, launched in 2009, has worked to establish a model for clean energy development in islands across the world, with specific support for USVI planning (Lantz et al. 2011).

As of mid-2017, there existed a variety of reports describing the overall environment and tensions in the USVI. These include an overview of environmental issues in the USVI (Noori and Taylor 2011), a Comprehensive Economic Development Strategy (U.S. Virgin Islands Bureau of Economic Research 2014), a 2040 Comprehensive Transportation Master Plan Report (USVI Department of Public Works 2014), a recent summary of climate change impacts on the Territory (Environmental Protection Agency 2016), and the 2016-2021 WAPA Strategic Plan (Virgin Islands Water and Power Authority 2016), among others.

1.1 The Hurricanes of 2017

In September 2017, two Category-5 hurricanes wreaked havoc on the infrastructure and welfare of the USVI; for details of these extreme weather events, see the final report of the USVI Hurricane Recovery and Resilience Task Force (2018).

Hurricane Irma. Hurricane Irma made landfall in the USVI between September 6-7, 2017 and catastrophically affected the islands of STT and STJ. Irma was recorded as the strongest observed hurricane in the Atlantic basin—in terms of maximum sustained winds—since Hurricane Wilma in 2005. Hitting the USVI as a Category-5 hurricane, Irma peaked with maximum sustained winds at 180 mph and a minimum pressure of 914 mbar. Irma caused catastrophic damage to the USVI infrastructure—specifically to buildings and critical utility infrastructure, including water, wastewater, telecommunications, and the energy grid—with heavy wind, rain, and flooding. Irma killed four residents and at the time was the fifth costliest Atlantic hurricane on record (National Hurricane Center 2018).

Hurricane Maria. Hurricane Maria hit the USVI island of STX during the night of September 20, 2017, just two weeks following the direct hit of Irma in STT and STJ. Maria was also a Category-5 hurricane with maximum sustained winds peaking at 175 mph and a minimum pressure of 908 mbar. (However, operators at Limetree Bay Terminals stated recording wind gusts at 240 mph during the early morning of September 20.) The storm produced heavy wind, rain, and flooding and killed three residents. In a 2017 article in Governing magazine, USVI Congresswoman Stacey Plaskett stated that the storm damaged or destroyed 90% of homes and over 13,000 homes lost roofs (Wogan 2017).

Collectively, the two storms caused incredible damage. According to the USVI Hurricane Recovery and Resilience Task Force (2018), “Total damage is estimated at $10.7 billion: $6.9 billion to infrastructure, $2.3 billion to housing, and $1.5 billion to the economy.”

FEMA Response. The Governor of the USVI, Kenneth Mapp, requested an expedited major disaster declaration on September 20, 2017, and President Trump declared a major disaster in the USVI territory the same day (Federal Emergency Management Agency 2017c). The declaration by the President made federal assistance available to affected residents and households, and it also made debris removal and emergency protective measures “available to territory and eligible local governments and certain private nonprofit organizations on a cost-sharing basis for all islands in the territory of the U.S. Virgin Islands" (Federal Emergency Management Agency 2017a). Because these storms also caused extreme damage to the island of Puerto Rico as well as Florida, Federal response efforts were stressed by the size and scope of the need for assistance. A complete timeline of preparations and responses is available from the Federal Emergency Management Agency (2017b).

The operating framework for the Federal Emergency Management Agency (FEMA), summarized in Appendix A.2, involves leveraging a variety of federal agencies with expertise in areas of specific need. For example, the Department of Energy (DOE), who has actively led efforts for the EDIN project for more than a decade, was called in to coordinate assessment and recovery efforts related to the energy infrastructure. In addition, the Office of Infrastructure Protection (IP) within the Department of Homeland Security (DHS) has taken an active lead in infrastructure assessment through its Protective Security Advisor (PSA) program.

At the request of FEMA, researchers at the Naval Postgraduate School (NPS)—see Appendix A.3 for background—were asked on December 18, 2017 to conduct modeling and analysis of (a) current and future energy systems in the USVI, along with (b) an assessment of the resilience of interdependent USVI lifeline infrastructure systems. Moreover, NPS researchers were asked to support coordination, training, and convening activities with local utilities and government representatives to strengthen the resilience of the territory overall. This report is the first of these efforts to provide preliminary technical assessment on infrastructure resilience in the USVI.

1.2 Achieving Critical Infrastructure Resilience for the USVI

Efforts for response and recovery from disasters such as those imposed by the 2017 hurricanes often focus on the concept of *resilience*, which has been prevalent in policy discussions of national security and emergency preparedness for more than a decade. As originally recognized in the 2007 National Strategy for Homeland Security (p. 27): "We will not be able to deter all terrorist threats, and it is impossible to deter or prevent natural catastrophes. We can, however, mitigate the Nation's vulnerability to acts of terrorism, other man-made threats, and natural disasters by ensuring the structural and operational resilience of our critical infrastructure and key resources." The notion of *operational resilience* requires "an approach that centers on investments that make the system better able to absorb the impact of an event without losing the capacity to function" (p. 28).

Since Hurricanes Irma and Maria, there have been several ongoing efforts across the USVI to recover and adapt critical infrastructure. Due to the outright destruction caused by the storms, these efforts address all lifeline infrastructure sectors. Achieving critical infrastructure resilience to future catastrophes requires guidance and coordination across these sectors, the GVI, FEMA, and numerous other stakeholders.

1.2.1 The USVI Governor's Recovery and Resilience Task Force

Following the hurricanes, Governor Mapp convened a Task Force consisting of "Territorial agency heads, senators, federal partners, business leaders, subject matter experts, and active members of our community. Their mandate was to present a report that lays out the best path forward to rebuilding and protecting our communities for the long-term" (USVI Hurricane Recovery and Resilience Task Force 2018, p. 5). One year after Hurricane Irma, on 6 September 2018, the Final Report of the USVI Hurricane Recovery and Resilience Task Force (2018) was published. It contains an accounting of the many problems that existed in the Territory before, during, and after the storms, and it lists recommendations "for the long-term recovery to improve critical infrastructure and public services and make businesses more resilient to future storms and other natural disasters" (USVI Hurricane Recovery and Resilience Task Force 2018). Specifically, the report contains more than 270 pages of data, images, and figures that ultimately support 228 proposed initiatives spread across a variety of infrastructure sectors: Climate Analysis (5), Energy (17), Private Sector Communications (14), Public Sector Communications (11): Transportation (24), Water (11), Solid Waste and Wastewater (26), Housing and Buildings (11), Health (21), Vulnerable Populations (12), Education (20), Economy (9), Non-profit, Philanthropy, and Voluntary Organizations (6), and Government Response (41).

The initiatives proposed by the Task Force make sense individually, but collectively they are overwhelming. Many of the standalone initiatives represent a massive undertaking. For example, as the first initiative for potable water, the report identifies a need to "Harden and rehabilitate the existing distribution system" despite a recognition that there are over 600 miles of water mains among the three main islands. Additional details of this initiative only make the task more daunting; the report states: "WAPA will rehabilitate the existing problem areas using federal funds through a combination of pipe replacement and pipe inspection and repair to fix high rates of leakage. WAPA will also inspect and assess the distribution network to ensure that pipelines are minimally threatened by trees, roads, and other infrastructure failure, as well as work with the Department of Public Works to ensure that water mains running under and alongside roads are securely installed. Finally, the utility will complete a Supervisory Control and Data Acquisition (SCADA) system to better control and monitor the distribution system" (USVI Hurricane Recovery and Resilience Task Force 2018, pp. 119-120).

With so much to be done, it is hard to know how to prioritize efforts, particularly when personnel and resources are limited. Among the 228 initiatives, the Governor's Office is listed as the primary entity responsible for executing 40 of them, and it is listed as the supporting entity for another nine initiatives. WAPA is listed as the primary entity responsible for 23 initiatives, with a supporting role for another six initiatives. Other government agencies are similarly tasked with a formidable amount of work.

1.2.2 The Need for an Operational View of Resilience

Prioritizing FEMA recovery work, initiatives from the Governor's Task Force, and the numerous other activities onging in USVI is an important task. Setting priorities for infrastructure resilience starts with two key recognitions.

First, it is important to understand critical infrastructure not merely as a list of important assets (e.g., facilities, cables, pipes, etc.), but *as a system of components that work together to deliver function*. It is not just the availability of assets, but how they are connected together and function as a system that determines, for example, whether the lights stay on or water flows. Managing infrastructure as a list of assets and key facilities (even if they are geo-located on a map) can help with shared awareness, but it alone will not help government officials or decision-makers understand how these systems will behave or potentially fail when stressed. Nor will it help them determine whether hardening existing assets or adding new ones will result in a more resilient system. Overall, there is a growing recognition that resilience is not about what a system *has*, it is about what the system *does* in anticipation and response to potentially disruptive events (Hollnagel et al. 2006; Eisenberg 2018).

A second important recognition is that *the behavior of infrastructure systems is the result of* *active management*—often by a mix of humans and/or automated technologies—in order to meet some overall service objective. In the short term and in response to disruptive events, this objective is often "minimize service outage," but over the longer term can be "minimize cost" or "maximize profit," particularly for infrastructures that are owned by private entities. These decision-making entities—we refer to them as *infrastructure operators*—are constrained in what they can do because of limited equipment, personnel, or other resources. Decision-making about the operation of an infrastructure system requires them to reconcile what they want (i.e., their objectives) with what they can do (i.e., their constraints).

Thus, the starting point for assessing how critical infrastructures respond to disruptive events (and in turn, how to improve this response) is to take an *operational view* of the drivers and constraints on infrastructure function. This operational view includes engineering, economic, and regulatory knowledge with enough detail to explain how infrastructure systems may realistically respond to any changes in infrastructure design and management (see Alderson et al. 2015, for a discussion).

1.2.3 Barriers to Resilience

Because an operational view of USVI critical infrastructure is still unavailable to many stakeholders, systems remain brittle despite best efforts to improve their resilience. In the aftermath of Hurricanes Irma and Maria, it is the shared goal of the Federal government, Territorial government, and local communities to 'build back better' and survive future disasters. However, significant research and practical experience teach us that building back better is no simple task, and decisions that superficially appear to improve infrastructure resilience may only exacerbate problems. New vulnerabilities arise when operational decisions are mismatched across critical infrastructure systems and people work at cross purposes (Woods and Branlat 2011). Flynn (2015), Alderson (2015, 2018), Seager et al. (2017) and others categorize four barriers to resilience that stymie best efforts to build back better.

Barrier 1: We don't fully understand how vulnerable we are. The owners, operators, or communities who manage infrastructure often do not have complete knowledge about their vulnerabilities, creating the potential for disaster. Practically speaking, it is almost impossible to predict all the ways in which infrastructure systems can fail. This is often due to dependencies that are revealed only when things go wrong. Communities can overcome this barrier when stakeholders have an operational view of infrastructure that recognizes both the objectives and constraints shaping system behavior.

Barrier 2: We don't know how best to create resilience. Even when communities know their vulnerabilities, there are tradeoffs and tensions between different mechanisms to achieve resilience, making prioritization difficult. For example, no single electricity generation technology—whether it burns fossil fuels or uses renewable sources like sunlight—is resilient to all surprises. Instead, a more resilient energy system has the ability to switch between fossil fuels and solar photovoltaics when needed. Ensuring flexibility in all critical infrastructure is challenging, but communities can overcome this barrier when they implement a balanced and coordinated response that weighs stakeholder objectives with operational constraints across multiple critical infrastructure systems. Again, an operational view is necessary for success.

Barrier 3: We don't have incentives to create resilience. Even when there is consensus on how to achieve resilience, we sometimes lack appropriate economic incentives for action. It can be difficult to justify spending to mitigate a situation that has never happened before, particularly when those funds can address immediate needs, and our attention is often focused on the most recent disaster. The problem can be even worse, as noted by Flynn (see National Infrastructure Advisory Council 2015, p. 25): "There are actually disincentives for resilience investment. Everybody is expecting that in a large disruptive event the Federal Government will come in and make them whole. Why should infrastructure owners invest their limited resources—already stretched too thin to support daily maintenance and operations—to invest in a 'what if' that, if the 'what if' does happen, will ultimately lead to generous checks being written out of Washington? This moral hazard is creating a real barrier to investing in mitigation." Moreover, even when large amounts of funding are available for restoration and recovery, the rules and/or metrics for deploying those funds are sometimes misaligned with resilience goals, particularly when there is time pressure to move quickly or they restrict investment to the same types of solutions that existed previously. Communities can overcome this barrier when they focus on investments that improve system operation during *both* routine circumstances and unexpected disruptions.

Barrier 4: We don't know how to govern for resilience. Finally, even when incentives are in place to invest in resilience, governance barriers can undermine successful implementation. As infrastructure systems undergo rapid change after a disaster, the organizations that own, operate, and regulate them may not change accordingly. Moreover, it is difficult to maintain the political will for balanced incentives that support resilience. Mismatch between infrastructure governance and infrastructure operation can have long-term consequences that undermine preparedness for the next disaster. Communities can overcome this barrier when they recognize that infrastructure adaptation also requires social adaptation. This social adaptation is centered on an operational view of resilience: programs that adapt built infrastructure systems also need to adapt organizations and governance bodies to support them.

Overall, the key point is that stakeholders need an operational view of 'how things work' to overcome barriers to resilience.

1.3 Objective and Organization of this Report

The objective of this report is to provide FEMA and other stakeholders with an operational view of 'how USVI lifeline infrastructures work' and offer recommendations to overcome barriers to critical infrastructure resilience. This report achieves this objective in several ways.

1. Explaining the structure, function, and tensions associated with critical infrastructure that were chronic problems *prior* to the hurricanes. The four lifeline infrastructure systems studied in this report are energy, with emphasis on electricity (Section 2), water (Section 3), transportation (Section 4), and telecommunications (Section 5). Each of these systems suffered from chronic challenges to their ongoing management *prior to the hurricanes of 2017*. Our analysis includes detailed descriptions of installed infrastructure, infrastructure condition, system structure, system function, management activities, markets, and long-term plans that influenced their operation leading up to the hurricanes. As is often the case throughout the U.S., few individuals beyond the system operators themselves actually have an operational view of 'how things work'. This knowledge is often limited beyond their particular system or sector despite the recognition that knowing how things work can be critical to crisis response across interdependent systems.

2. Documenting hurricane response, recovery, and mitigation activities for these infrastructure systems *after* the hurricanes. Both the immediate response and longer-term recovery of lifeline infrastructure systems will have a profound effect on their resilience. Our analysis documents ongoing activities to improve these critical infrastructure systems in 2018. This is intended to be neither comprehensive nor authoritative, particularly because what constitutes 'ground truth' is rapidly evolving. Instead, this report contributes to the continued shared awareness among various stakeholders and supports discussions regarding current efforts to enhance resilience.

3. Discussing these changes in the context of potential barriers to resilience. This report concludes by framing past and current infrastructure operations within the context of the four barriers to resilience, and it offers ways to overcome them. There is no clear resilience objective guiding the rapid changes ongoing in USVI energy, water, transportation, and communication systems. Thus, it is unclear how current infrastructure resilience activities will affect the long term operation of these systems. By providing an operational view, we can identify how current and planned resilience activities address barriers to resilience. We provide concrete approaches to overcome barriers (where they exist) and open questions for research (where they do not yet exist).

2 USVI Energy Systems

USVI energy infrastructure includes fuel delivery systems and electric power systems. This report focuses on the operation of USVI electric power systems, including primary energy sources, electricity generation, distribution, and use. STT and STJ share a single power system, whereas STX has its own independent power grid. Electric power infrastructure is owned, operated, and maintained by the Virgin Islands Water and Power Authority (WAPA). WAPA is an autonomous government public utility that serves approximately 55,000 customers throughout the Territory.

The rest of this chapter is organized to present the features of the STT/STJ and STX power systems relevant for understanding their resilience. Grid infrastructure is discussed alongside key tensions that affected STT/STJ and STX grids prior to the hurricanes and continue to make operations difficult after the hurricanes. Hurricane impacts are also briefly discussed to show current disaster mitigation and recovery efforts.

2.1 Electric Power Infrastructure on STT/STJ

The STT/STJ power system serves the islands of St. Thomas, St. John, Water Island, and Hassel Island. All fuel and generation infrastructure for the STT/STJ power system is located on STT, where STJ, Water Island, and Hassel Island are served electricity via underwater power lines.

STT/STJ Fuels and Working Fluids. The STT/STJ power grid receives fuel oil and liquefied propane gas (LPG) via tanker ship at the port in Charlotte Amalie, STT. From port, fuel is moved by truck to WAPA storage facilities in Krum Bay, STT via three subcontracted gas trucking companies, Antilles Gas, St. Thomas Gas co., and ProGas. LPG is also accessible via an offshore Very Large Crude Carrier (VLCC) barge near STT called Berge Summit. Here, LPG is transferred to smaller ships for direct delivery to the WAPA Krum Bay storage facilities. WAPA fuel storage is located near the Randolph Harley Generating Station (RHGS). Fuel in WAPA storage is fed directly to turbines via fuel delivery pipelines.

WAPA fuel reserves at Krum Bay include fuel oil storage to serve normal electric power demands for 10 to 14 days (exact fuel oil volumes unavailable) and LPG storage capacity for approximately 18 days (10 tanks, 13,350 m^3 volume).

In addition to fuel, RHGS also requires water for cooling and power generation with steam turbine generators and waste heat recovery systems. Water for power generation is desalinated sea water produced at the Seven Seas reverse osmosis plant co-located at the RHGS. Although Seven Seas is a private company, it has standing contracts with WAPA operations. Seven Seas provides water for generation via a dedicated water main that serves the power plant. WAPA further demineralizes this water prior to use in turbine systems.

Figure 2. Harley Power Plant. Photo: VI Consortium.

STT/STJ Generation. The Randolph Harley Generating Station (RHGS) is the only fossil fuel power plant in the STT/STJ power system (Figure 2). RHGS is located just south of Cyril King Airport in Krum Bay, STT and has six active gas turbine generators and three blackstart generators for emergency operations. All generators produce electricity at the rated voltage of 13.8kV and are electrically connected to the STT/STJ power system at the Krum Bay bus. RHGS total generating capacity is estimated to be approximately 131-140MW depending on turbine dispatch and maintenance schedules.

The majority of RHGS generators use no. 2 fuel oil as a primary fuel, where only one generator set (Unit 22/26) is capable of using LPG as a primary fuel. Fuel use data for RHGS turbines is currently unavailable.

The STT/STJ power system also has three sources of renewable energy generation. Two photovolatic power plants are located on STT at Estate Donoe (4.2MW capacity) near Tutu substation and Port Authority (0.45MW capacity) near Krum Bay. The third is ~5-6.9MW of net metering also from photovoltaics located across multiple locations in STT and STJ.

Gas Turbine Generators STT/STJ Power System			
Unit	Fuel Type	Capacity (MW)	Unit Type
14	#2 Fuel Oil	15.1	Hitachi Generator/GE Turbine MSS001
15	Dual (#2 or LPG)	26.6	GE Generator/GE Turbine MSS001
22/26	Dual (#2 or #6)	26	TM2500 + GEN 6
23	#2 Fuel Oil	42	GE PG 6581
25	#2 Fuel Oil	22	TM2500
Blackstart Emergency Generators			
Unit	Fuel Type	Capacity (MW)	Unit Type
15/18	#2 Fuel Oil	0.15	John Deere ADP ULI150
9B	#2 Fuel Oil	0.3	Communings NTA855-G2
22	#2 Fuel Oil	0.35	Elliot MagneTek 350RD

Figure 3. The Randolph Harley Generating Station has six active gas turbine generators (turbines 22 and 26 work in parallel on the same electrical bus) and 3 blackstart generators for backup. Source: RW Beck (2010).

STT/STJ Transmission and Distribution (T&D). The STT/STJ T&D system functions at two primary voltage levels. Power is generated at 13.8 kV and stepped up to 34.5 kV for transmission across STT. There are five substations: Krum Bay, Donald Francois (also called Long Bay), Tutu, East End, and Solar. All substations on STT are connected by 34.5 kV above ground and underground sub-transmission lines that form a loop around the island. The sub-transmission loop starts at Krum Bay connecting to Donald Francois via an underground power line. Donald Fracois connects to East End, East End connects to Tutu, and Tutu connects back to Krum Bay via aboveground cables. Krum Bay and Tutu substations are also connected to the Solar substation located near the Estate Donoe PV power plant.

Power is distributed with 13.8kV feeders within STT and to STJ, Water, and Hassel Islands. On STT, there are seven above ground power line feeders serving load: #5, #6, #7, #8, #9, #10, and Ridge Road (Figure 11). Feeders #5-#10 connect to the Krum Bay bus and

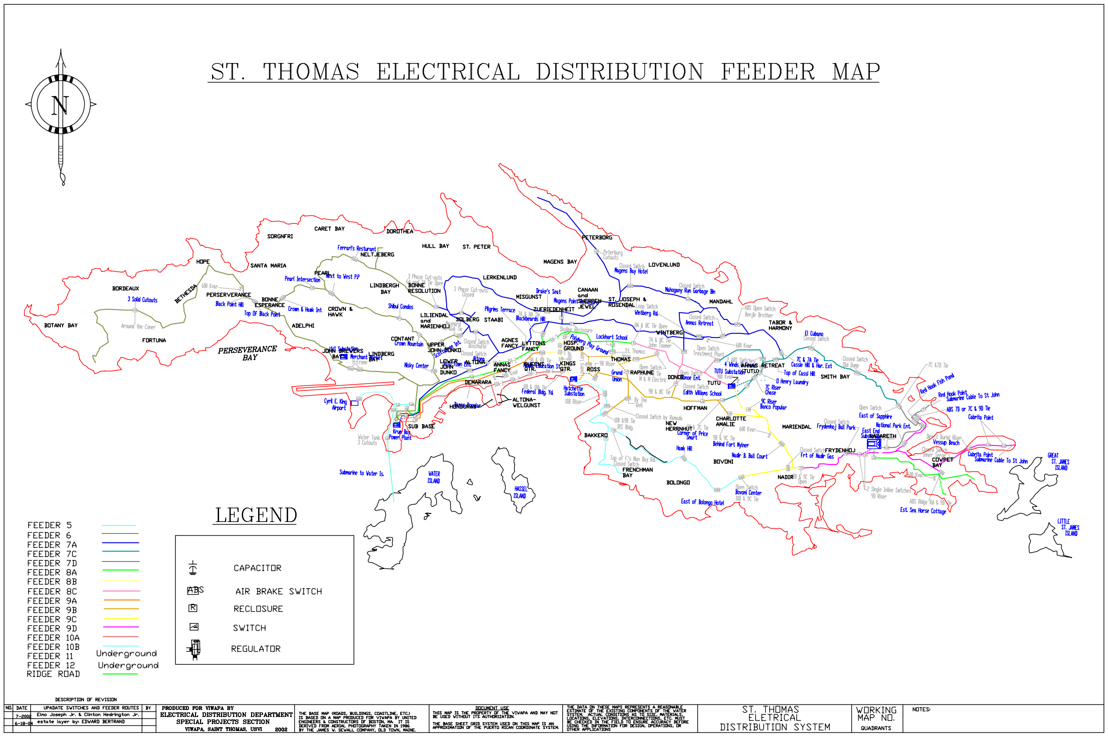

Figure 4. STT Feeder Map from 2012 showing substations and primary feeders. Note: Donald Francois substation is listed as Long Bay and Solar substation is not listed. From: Virgin Islands Water and Power Authority (2012)

Ridge Road connects to East End. Feeder #5 serves several critical loads near Krum Bay, including the Cyril E. King Airport, the Krum Bay LPG station, Seven Seas Water Plant, WAPA fuel dock, and Water island. Feeder #6 serves local community loads on STT near Krum Bay on the western part of STT. Feeder #8 serves several critical loads between Krum Bay and Donald Francois substations, including the Medical Arts Complex and the Knut Hansen Hospital grounds. Feeder #10 serves regions in the southeast of STT, including WAPA offices, Estate Thomas Medical Complex, and several hotels and schools. The Ridge Road feeder serves the extreme south east of the island, including the Ritz Carlton Hotel. Feeders #7 and #9 serve the rest of the STT, forming a large loop connecting Krum Bay, Donald Francois, East End, and Tutu substations and serving a number of critical loads.

Feeders #7 and #9 also connect the islands of STT and STJ via underwater power lines

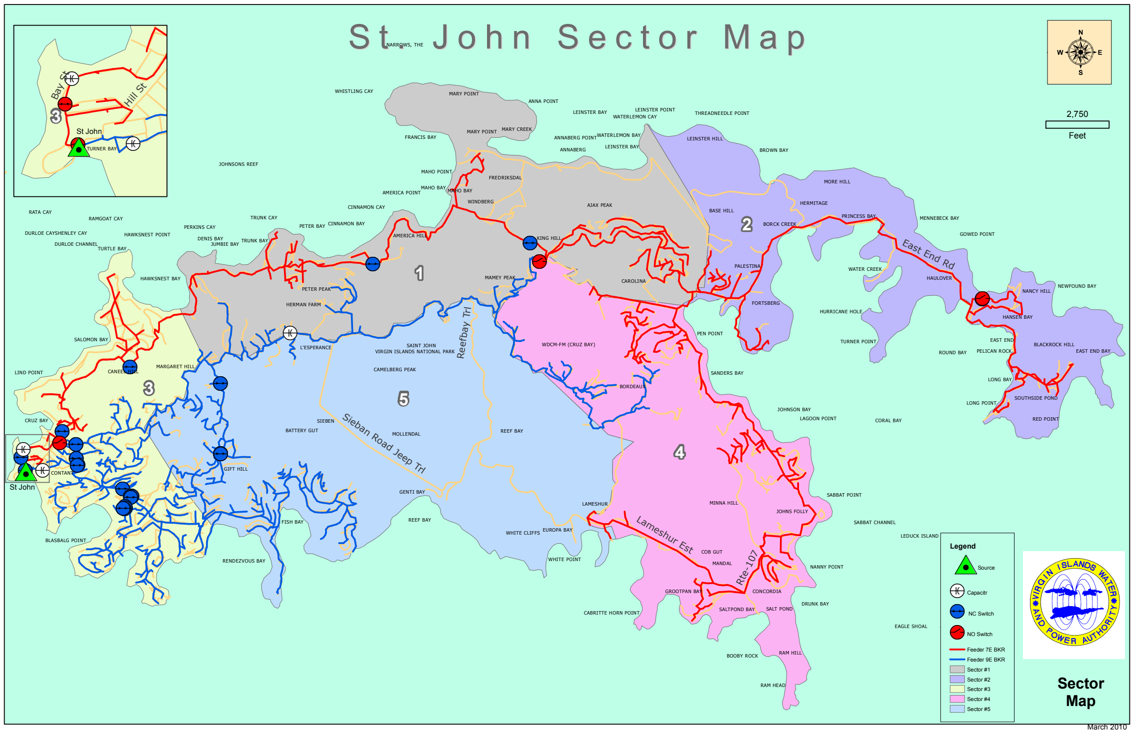

Figure 5. STJ Feeder Map from 2010 showing primary feeders #7 and #9. From: Virgin Islands Water and Power Authority (2010)

between Red Hook, STT and Frank Bay, STJ. The only substation on STJ is Echo Bordeaux in Frank Bay on the far western coast of the island. All loads in STJ are served by power generation in STT transmitted to this substation. Power is routed on STJ to Feeder #7 serving northern, eastern, and southern customers and Feeder #9 serving western customers (see Figure 5).

STT/STJ Loads. Peak and minimum loads in the STT/STJ power system vary by month in a typical year (e.g., see Figure 6). In a typical year, peak loads across all months remain relatively stable with the greatest electric power demands occurring in the middle of summer. Minor fluctuations in needs suggest a general operating range for generation assets, approximately between 59-66MW for all peak demands.

STT/STJ also has stable maximum and minimum generation needs for each year from 2014-2017 (Figure 7). From 2014 to 2017, all peak loads occurred in the summer months of June

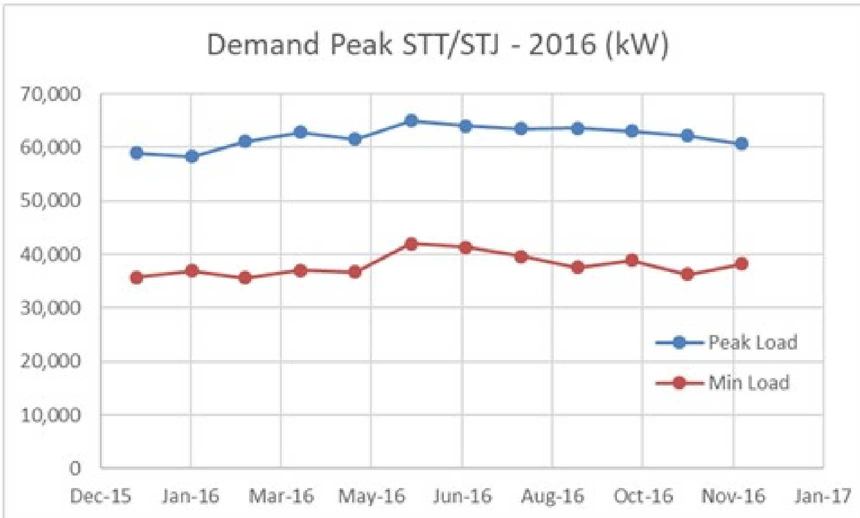

Figure 6. Monthly peak and minimum load in STT/STJ for the year of 2016. Data provided via Personal Communication (2018).

	Max and Min Loads in STT/STJ							
	2014		2015		2016		2017	
	MWh	Month	MWh	Month	MWh	Month	MWh	Month
Max Monthly Generation	38,971	JUL	38,469	OCT	39,862	JUL	39,423	JUL
Min Monthly Generation	32,439	FEB	32,927	FEB	34,289	FEB	31,639	FEB
	2014		2015		2016		2017	
	kW	Month	kW	Month	kW	Month	kW	Month
Peak Load	66,000	JUL	65,200	JUL	65,000	JUN	65,700	JUN
Min Load	26,600	MAY	24,600	AUG	35,600	MAR	31,500	APR

Figure 7. Peak and minimum generation and loads in STT/STJ from 2014 to 2017 Data provided via Personal Communication (2018).

and July, and maximum generation needs were most common in the month of July. February requires the least generation assets due to having fewer days than any month. Minimum loads occur in shoulder months of March and April and summer months like August. Overall, the total generation requirements for STT/STJ across all seasons remains “flat" compared to less temperate regions of the US. This is significant for matching generation requirements to loads, as a flatter profile does not require additional generation capacity that is only used to serve demands differences across seasons.

2.2 Electric Power Infrastructure on STX

Superficially, the STX power grid has many similarities to the STT/STJ power grid. However, numerous idiosyncratic differences in fuels, generation, transmission and distribution, and loads may lead to large differences in STX operational resilience.

STX Fuels and Working Fluids. STX power grid receives fuel oil and LPG in a similar fashion to the STT/STJ power grid. All fuel is imported by tanker ship to the port in Christiansted, STX. From port, fuel is moved by truck to WAPA storage facilities in Estate Richmond, STX via the same gas trucking contractors (Antilles Gas, STX/STT Gas, and ProGas). LPG is also accessible via Berge Summit tanker ships. STX WAPA fuel storage is near the Richmond Generating Station (RGS). Fuel in WAPA storage is fed directly to turbines via fuel delivery pipelines.

WAPA fuel reserves at Estate Richmond, STX include fuel oil storage to serve normal electric power demands for 10 to 14 days (exact fuel oil volumes unavailable) and LPG storage capacity for approximately 19 days (8 tanks, 10,400 m^3 volume).

In addition to fuel, RGS receives water for cooling and power generation like the RHGS on STT. Water for power generation is desalinated sea water produced at the Seven Seas reverse osmosis plant co-located at the RGS. Seven seas provides water to the RGS via a dedicated water main that serves the power plant. WAPA further demineralizes produced water prior to use in turbine systems.

STX Generation. The Richmond Generating Station (RGS) is the only fossil fuel power plant in the STX power system (Figure 8). The RGS is located in Christiansted, STX on the eastern part of the island and has 6 active turbine generators and one blackstart generator (Figure 9). Units 10 and 11 are steam turbine generators that use water as a working fluid. These two units are also the only turbines that generate electricity at 13.2 kV. All

Figure 8. Richmond Power Plant. Photo: VI Consortium.

other generators are combustion turbine generators that generate electricity at 13.8 kV. Total generating capacity for the six turbines is estimated approximately between 117-140MW depending on dispatch, fuels used, and maintenance schedules.

RGS generators use no. 2 fuel oil and LPG as a primary fuel. All combustion turbine generators at RGS are upgraded to run via dual fuel intake for both no. 2 fuel oil and LPG. Since October 2016, units 16, 17, and 20 have run almost exclusively on LPG (Figure 10). Total fuel use at RGS from October 2016 to October 2017 was approximately 26 Mbbls (million barrels) of LPG and approximately 0.3 Mbbls of #2 fuel oil.

The STX power system also has three sources of renewable energy generation. Two photovolatic power plants on STX are located at Estate Spanish Town (4MW capacity) near Midland substation and one at the Almeric L. Christian Federal Building (0.47MW capacity) north of the RGS. The third is approximately 5-6MW of net metering located across multiple locations across STX.

STX Transmission and Distribution (T&D). The STX T&D system functions at four primary voltage levels. Electricity is generated at 13.2 kV and 13.8 kV and stepped up to 69

Gas Turbine Generators STX Power System			
Unit	Fuel Type	Capacity (MW)	Unit Type
10	#2 Fuel Oil	10	Worthington STG
11	#2 Fuel Oil	19.1	GE STG
16	Dual (#2 or LPG)	20.9	GE MS5001P CT
17	Dual (#2 or LPG)	21.9	Alstom
19	Dual (#2 or LPG)	22.5	GE5001
20	Dual (#2 or LPG)	22.5	GE5001

Blackstart Emergency Generators			
Unit	Fuel Type	Capacity (MW)	Unit Type
--	#2 Fuel Oil	0.75	GE6F09802

Figure 9. The Richmond Generating Station has 7 active generation units – two steam turbine generators (Units 10 and 11) and four gas turbine generators, and one blackstart generator for backup. Data provided via Personal Communication (2018).

Fuel Consumption Richmond Generating Station (Oct 2016 - Oct 2017)	
Propane	bbl ($x10^6$)
Unit 16	5.104
Unit 17	5.08
Unit 20	15.43
No. 2 Fuel Oil	bbl ($x10^6$)
Unit 10	0
Unit 11	0.01
Unit 16	0.009
Unit 17	0.061
Unit 19	0.101
Unit 20	0.127

Figure 10. Fuel consumption at the Richmond Generating Station is dominated by LPG for Units 16, 17, and 20. no. 2 fuel oil is still used in limited quantities by all turbines. Data provided via Personal Communication (2018).

kV for transmission across the island. There are two substations, Richmond in the east near Christiansted and Gregory E. Willocks (also called Midland) in the center of the island. There are also two electrical buses at 69 kV; South Gate bus near the RGS and Christiansted and Frederiksted bus on the west coast of the island. The 69 kV power lines form an electrical loop, with links from Richmond to Midland substation, Midland to Fredriksted bus, and Frederiksted to Richmond. Richmond is also connected to South Gate bus via 69 kV lines.

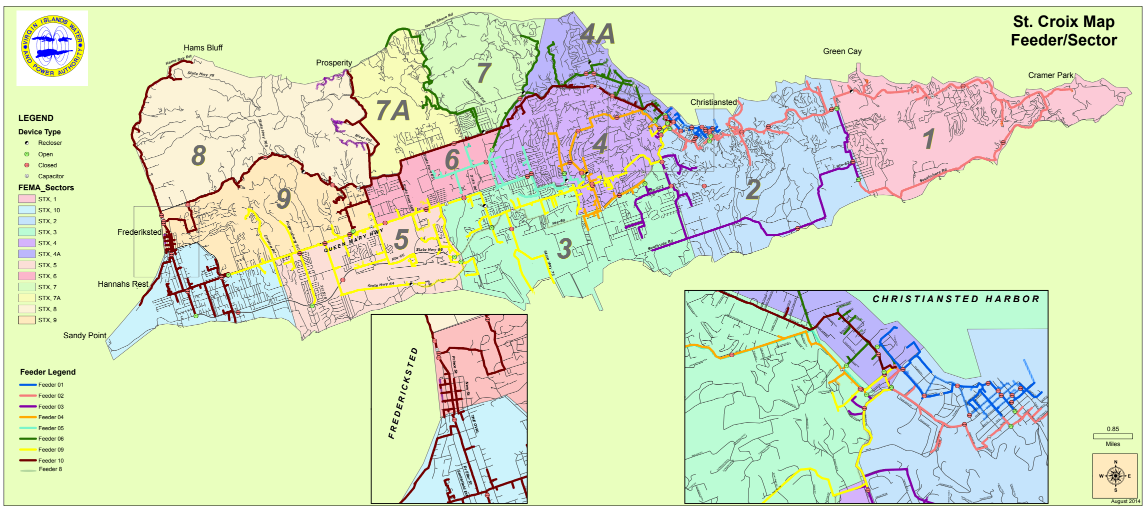

Figure 11. STX Feeder Map from 2014 provided by WAPA. Richmond substation and Frederiksted bus are located in the Christiansted Harbor and Frederiksted call out boxes, respectively. Note: Feeder numbers do not match colored FEMA sectors. From: Virgin Islands Water and Power Authority (2014)

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From substations, power is distributed with 13.8 kV and 24.9 kV feeders (Figure 11). On STX, there are nine above ground power line feeders serving load: #1, #2, #3, #4, #5, #6, #8, #9, and #10. Feeders #1-#6 are 13.8 kV and Feeders #8-#10 are 24.9 kV. Feeders #6 and #8 also have underground portions.

Feeders #1, #5, and #6 connect to the Richmond Substation. Feeder #1 serves local communities in Christiansted. Feeder #5 serves the central portion of the island near Kingshill with several critical loads, including a National Guard base, police station, WAPA offices, and a shopping mall. Feeder #6 serves the northern portion of the island including the Salt River Bay National Historic Park.

Feeders #2, #3, and #4 connect the Richmond substation with South End bus and local communities. Feeder #2 serves the far eastern portion of the island including the STX radio station. Feeder #3 serves the Golden Rock Shopping Center in Richmond and southeastern portion of the island. Feeder #4 serves the Bellevue area inland from Richmond.

Feeders #8, #9, and #10 connect the Richmond substation to the Midland substation and local communities. Feeder #8 is underground and serves several critical loads in the southwestern portion of the island including Harry Rohlsen Airport and a Navy Tracking Station. Feeder #9 serves the southwestern region surrounding the airport, including an industrial park, the Golden Grove Correctional Facility, and the University of the Virgin Islands campus. Feeder #10 serves the west and northwestern portion of the island.

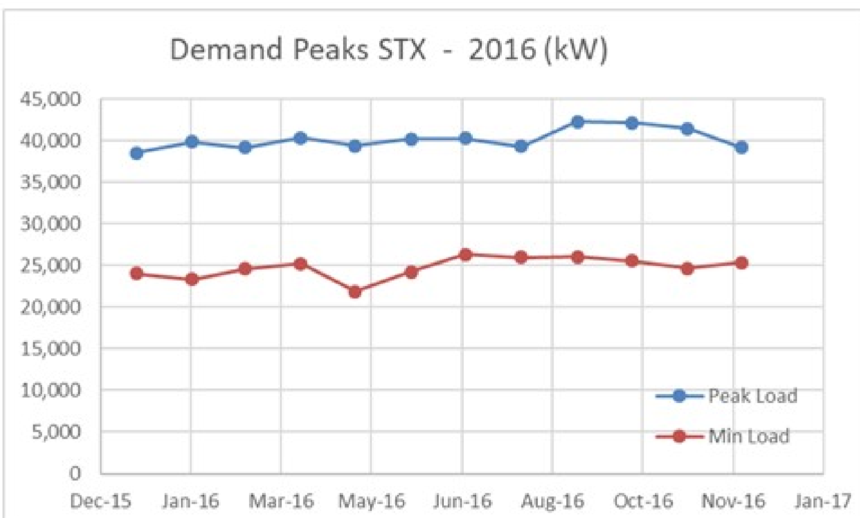

Figure 12. Monthly peak and minimum in STX for the year of 2016. Data provided via Personal Communication (2018).

STX Loads. The load profile for STX is similar to that for STT/STJ, but the total generation and peak load is approximately 50% of STT/STJ. STX has its highest peak loads near the end

	Max and Min Loads in STX							
	2014		2015		2016		2017	
	MWh	Month	MWh	Month	MWh	Month	MWh	Month
Max Monthly Generation	25,935	OCT	24,807	OCT	24,736	OCT	24,165	JUL
Min Monthly Generation	21,883	FEB	21,161	FEB	21,169	FEB	19,772	FEB
	2014		2015		2016		2017	
	kW	Month	kW	Month	kW	Month	kW	Month
Peak Load	43,700	JUN	41,270	OCT	42,270	SEP	40,410	AUG
Min Load	20,990	MAY	22,500	APR	21,860	MAY	22,620	JAN

Figure 13. Peak and minimum generation and loads in STX from 2014 to 2017. Data provided via Personal Communication (2018).

of summer (see Figure 12), where annual fluctuations in demand suggest a general operating range approximately between 37-44 MW for all peak demands. STX also has relatively stable maximum and minimum generation needs across years (Figure 13). From 2014 to 2017, October always required the most power generation to serve demands and minimum loads occured in May and April most frequently. The "flat" generation profile across the year suggests that it should be simpler in STX to match installed generation capacity to loads than in regions with less temperate climates and greater differences among seasons.

2.3 Tensions Affecting Power Grid Resilience Before the Hurricanes

STT/STJ and STX power systems share common resource, infrastructure, market, and customer issues that influenced their operational resilience before Hurricanes Irma and Maria.

2.3.1 Energy Sources for Electric Power Generation

The vast majority of electric power generation in the USVI relies on imported diesel, fuel oil (no. 2 and no. 6), and liquefied propane gas (LPG). WAPA also has renewable energy generation assets in the form of solar photovoltaics and net metering programs to harness household generation by electricity customers. USVI reliance on fossil fuels for electricity generation, alongside Territory-wide mandate to transition to clean energy, reveals important tensions influencing operational and planning decisions for WAPA.

Petroluem Fuel. Historically, STT/STJ and STX power systems relied on diesel fuel for power generation because they *had* a reliable source from a local petroleum refinery. The Hess Oil Virgin Islands Corporation (HOVIC) opened a refinery in Limetree Bay, STX in 1966. Since opening, the refinery was one of the 10 largest refineries in the world and served WAPA via fuel truck on STX. Hovensa LLC, a joint venture between Hess Corporation and Petroleos de Venezuela, took over the operation of this refinery in 1998. In the late 2000s, the refinery began to lose money due to reduced demand caused by the global economic slowdown and increased refining capacity in emerging markets (Cleveland 2012). By 2011, losses at Hovensa totaled $1.3 billion (Cleveland 2012) and the refinery stopped serving diesel fuel to WAPA (Gleason 2018). In 2012, the refinery closed.

WAPA now relies on a mix of imported no. 2and no. 6 fuel oil for electric power generation. No. 2 fuel oil is chemically similar to diesel, and was the primary fuel replacement when diesel became unavailable. WAPA has upgraded several turbine generators to run on no. 6 fuel oil and to have a dual-fuel intake systems that allow turbines to run on no. 2, no. 6, and a mix of fuels to save money and reduce emissions. Both fuel oils are refined prior to import and imported by Glencore.

The Hovensa refinery may still serve WAPA in the future. The refinery is now owned by Limetree Bay Terminals, LLC (LTB) and continues operation as a fuel storage terminal. LTB has approximately 30 million barrels of storage capacity, of which 10 million is crude oil and 20 million is distributed across fuel sources: clean gas, diesel fuel, jet fuel, and propane. Currently, LTB does not provide stored fuel to WAPA and has no known agreements to provide backup fuel in the event of an emergency. This may change if and when the refinery is brought back online. In early July 2018, ArcLight Capital Partners (LTB's parent company) announced plans to invest $1.4B to refurbish and restart the refinery, leading to 1,000 new construction jobs, 700 permanent refinery jobs, and the capacity to refine approximately 200,000 barrels per day of crude oil by January 2020 (Virgin Islands Consortium 2018).

Liquefied Propane Gas (LPG). WAPA is transitioning to using LPG as its primary fuel source for electric power generation to increase generator efficiency, save money, and reduce emissions. To achieve this, several power generating turbines were upgraded to have LPG fuel intake systems in addition to existing dual fuel oil intake systems (referred to as tri-fuel systems). Despite infrastructure upgrades, the transition to LPG has been slow due to failed contracts. Vitol Virgin Islands Corporation is responsible for supply and delivery of LPG. Vitol has withheld propane fuel supplies from WAPA in the past due to outstanding balances (Clark et al. 2018). WAPA continues to use higher-cost and less efficient fuel oil for electricity generation in addition to LPG.

Figure 14. Offloading LPG to VITOL LPG Terminal in Christiansted. Photo: St. Croix Source.

Renewable and Other Electricity Sources. There are no other conventional electricity generating sources in the USVI (e.g., nuclear or coal) and limited renewable energy generation compared to fossil fuels. Still, plans to significantly increase renewable energy generation capabilities across all islands have influenced the last decade of power system operation and planning by WAPA. In 2010, the USVI Territorial government signed a Memorandum of Understanding (MOU) with the U.S. Department of Energy's Office of Minority Economic Impact and the U.S. Department of Interior's Office of Insular Affairs, that same year, the VI Legislature enacted Act 7075. Both the MOU and Act 7075 outlined clean energy goals for the territory (Legislature of the U.S. Virgin Islands 2018). The MOU specified a 60% reduction of all fossil fuel use across the islands with a required 30% reduction for electric power generation (equivalent of 660,000 barrels of oil per year) by 2025 and Act 7075 required 30% renewables by 2015.

Two prominent plans were developed to achieve these goals. First, the National Renewable

Energy Laboratory (NREL) created the Energy Development in Island Nations (EDIN) USVI Energy Road Map detailing analysis of renewable energy and efficiency initiatives to reach this goal (Lantz et al. 2011). Second, WAPA developed an Integrated Resource Plan (IRP) released in November 2016 (Virgin Islands Water and Power Authority 2016). The EDIN-USVI road map guided the last 10 years of transition to a clean energy economy through energy efficiency and renewable energy technology development. EDIN-USVI projections show a combination of solar, wind, and other renewable technologies can produce electricity equivalent to 50% of total USVI power consumption across all three islands (Lantz et al. 2011). Specific plans for infrastructure installation, workforce development, and the decommissioning of fossil fuel power plants is provided in the WAPA IRP (Virgin Islands Water and Power Authority 2016).

Renewable energy now accounts for up to 20% of USVI electricity needs on a given day (depending on weather and customer demands) (Rhymer Sr. 2017). High penetration of renewable generation is primarily achieved via net-metering programs where household solar and wind systems sell electricity back to STT/STJ and STX grids. WAPA also owns and operates solar photovoltaics power plants and a few off-grid wind turbines. While solar power plants are well-documented, there is limited information regarding their technical output and operation of wind turbines.

Despite progress towards Territorial goals, WAPA continues to face, regulatory, engineering, and financial challenges that limit the deployment of renewable energy technologies. Regulatory challenges with the net metering program involve a 15% threshold on the maximum percentage of net metering generation for meeting 2025 clean energy goals. The net metering program has already reached its 15% penetration cap. This, coupled with outdated interconnection/permitting standards and practices make it difficult for WAPA to promote distributed generation without more effective system designs (e.g., with battery backup). The high penetration of renewables also creates system operation and management issues. Variable generation requires WAPA to continue to spin turbines to provide base load backup for solar, which wastes fuel with oversized turbine generators. There are also challenges with limited workforce availability to monitor and control grid operations. This is an increasing problem as greater renewable energy generation deployment adds greater complexity to grid operations.

2.3.2 Electric Power Generation and Distribution Infrastructure

Both STT/STJ and STX power grids have similar functional capability to serve customer loads. Likewise, the same reliability issues exist in both power systems.

Generation. System faults and operational issues at USVI generating plants account for an estimated 99% of WAPA power outages (Hedrington 2018). Reliability issues stem from a lack of power plant redundancy and operational flexibility.

Both STT/STJ and STX power systems lack redundant electric power generation infrastructure. STT/STJ and STX systems rely on a single, large generating facility that runs on fossil fuels (LPG and fuel oil) supported by smaller solar PV plants and net metering. The reliance on a single generating facility means any fault at the STT/STJ or STX power plant that trips generators can blackout an entire island and require up to two hours to bring the grid back online.

STT/STJ and STX power plants also lack flexibility in how they serve demand causing generation-load and voltage-frequency imbalances. Each facility is comprised of few, large electricity generating turbines oversized to serve loads much larger than STT, STJ, or STX require. This plant design mimics many power plants in the mainland U.S., and is most cost efficient when generators operate at maximum capacity to meet large, stable loads. However, the USVI is comprised of small and varying loads leading to inefficient generator operation. The oversized turbines often run at heat rates much lower than optimal, wasting primary fuels and working fluids (e.g., water for cooling). Also, variability in loads cause voltage-frequency issues, as few WAPA customers are large or constant enough (e.g., base load customers like industrial plants) for stable turbine operation and control. In the absence of base load customers, USVI generation infrastructure experiences dramatic swings that are difficult to match, causing inertial issues, generator faults, and blackouts.

Transmission and Distribution (T&D). From centralized generation plants, electric power is stepped-up to transmission (69kV) power lines and sub-transmission and distribution (34.5 kV, 24.9 kV, and 13.8 kV) power lines referred to as feeders to send electricity across islands. Together, USVI T&D systems have 737.8 miles of lines: 30.1 miles of 34.5 kV, of which 59% (17.7 miles) is underground and/or undersea; 106.6 miles of 24.9 kV, of which 15% (16.5 miles) is underground; and 601.1 miles of 13.8 kV, of which 7% (40.3 miles) is underground (Clark et al. 2018).

Some USVI power transmission and distribution systems lack redundancy which impacts customer access to electricity. In general, USVI transmission networks are robust to faults by having a redundant looped (meshed) structure to protect against blackouts and switches to transition customers from one feeder to another and/or protect critical loads. On the other hand, several feeders in STT/STJ and STX systems have a radial structure where all customers are served by a single power line. In these systems, the loss of a single feeder can cause all downstream customers to lose electricity. It should be emphasized that this issue is not special to the USVI, and impacts customer access to electricity in many T&D systems across the US.

2.3.3 Markets and Customers

The difficulties described above that impact WAPA power grid operations—maintaining secure fuel supplies, funding new renewable energy assets, decommissioning old infrastructure, and managing infrastructure faults that lead to blackouts—all impact WAPA's finances. Between 2012 and 2016, WAPA experienced shortfalls in revenue ranging approximately from 2-10% of expenses (BDO USA, LLP 2016). Trends in the USVI energy market, customer demographics, and customer loads suggest continuing economic issues.

Market Features. The historical average price of electricity in the USVI ranges from \$0.29 to \$0.32 per kWh, which is approximately three times the cost of electricity in the mainland U.S. (U.S. Energy Information Administration 2017). Prices in 2017-2018 were \$0.32 to \$0.35 for residential customers and \$0.38 for industrial customers (USVI Hurricane Recovery and Resilience Task Force 2018).

The high price is due to a number of surcharges for operational needs (e.g., line losses) and generating resources. The single largest surcharge is for electricity generation fuels called the Levelized Energy Adjustment Clause (LEAC) (Figure 15). The ability for WAPA to cover expenses with electricity sale revenues depends on the LEAC surcharge matching fuel prices. WAPA's single largest source of revenue is the LEAC and their single largest expense is fuel (see Figure 16). The primary reason claimed by WAPA for shortfalls in revenue for the 2012 to 2016 period is the LEAC price not sufficiently matching fuel market prices.

The high price based on surcharges also means that USVI electricity prices are highly volatile. Because the LEAC must match the cost of oil, it can shift significantly from year to year based on international markets (Figure 15). During the years of 2013 and 2014, residential electric power rates were as high as $0.52 per kWh (USVI Hurricane Recovery and Resilience Task Force 2018). Other surcharges are also based on variable costs like maintenance that can increase in the case of a disaster. It is well-established by the USVI Territorial government that electricity bills are one of the primary community stressors across the islands (Severe 2018).

Figure 15. Electricity sales in the USVI WAPA is dependent on the Levelized Energy Adjustment Clause (LEAC) surcharge matching fuel prices. Internal data shared with NREL in 2012 shows how WAPA matched the LEAC to the cost of oil. From 2012 to 2016, the LEAC has not matched the cost of oil, and is the primary reason for lost revenue stated by WAPA. Reproduced From Lantz et al. (2011).

Utility Customers and Distributed Generation. Electricity customers in the USVI are separated into four categories: residential, commercial, large industrial (including the USVI Territorial government), and public street lighting. For the last 10 years, the total number of electrical utility customers and total sales in kilowatt-hours to each customer category

	2018 (ending 10/01)		2017		2016		2015		2014	
Revenues (in thousands)	$	% Total	$	% Total	$	% Total	$	% Total	$	% Total
Levelized Energy Adjustment Clause (LEAC)	129,668	57	114,562	58	135,799	61	187655	69	241981	76
All Other (incl. sales and surcharges)	95,927	43	83,523	42	88,450	39	82655	31	78234	24
Total	225,595	--	198,085	--	224,249	--	270,310	--	320,215	--
Expenses (in thousands)	$	% Total	$	% Total	$	% Total	$	% Total	$	% Total
Fuel	94,881	47	123,007	47	125688	55	172210	59	231711	70
All Other (incl. production, admin, depreciation)	109,099	53	138,822	53	101441	45	119916	41	100835	30
Total	203,980	--	261,829	--	227129	--	292126	--	332546	--
Electricity Sales (in thousands)	kWh	% Total	kWh	% Total	kWh	% Total	kWh	% Total	kWh	% Total
Residential	142,834	37	228,987	37	224,268	35	211,753	34	219,402	34
Commercial	71,290	18	112,187	18	115,464	18	108,148	17	113,517	18
Government + Industrial	171,499	44	260,910	42	281,609	44	283,558	46	291,037	45
Street lighting	4,566	1	17,450	3	17,350	3	17,422	3	17,078	3
Total	390,189	--	619,534	--	638,691	--	620,881	--	641,034	--
Number of customers at year-end		Total (estimate)		Total (estimate)		Total		Total		Total
Total		55,555		56,741		54,881		54,881		54,917

Figure 16. Financial statements for WAPA from January 2014 to October 2018 showing total revenues, expenses, and sales. Significant losses in revenue are attributed to the Levelized Energy Adjustment Clause (LEAC) surcharge escalator not matching variable fuel prices. Likewise, expenses decreased due to reduction in fuel costs, making operations and management a larger portion of total expenses. Unfortunately, the total number of customers and electricity sales has not changed significantly during the same period (Virgin Islands Water and Power Authority 2018; BDO USA, LLP 2016)

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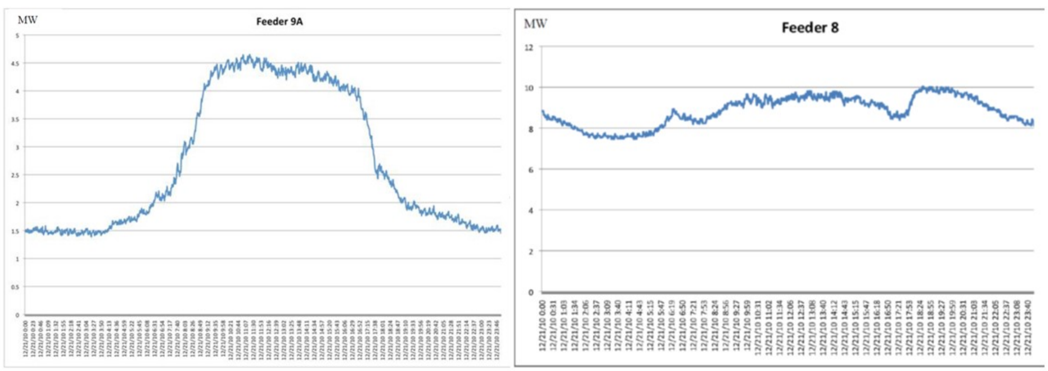
has remained stable across the islands: total number of customers: ~54-56,000; total sales: residential (~34-37%), commercial (~17-18%), industrial (~42-46%), and lighting (~1-3%) (see Figure 16).

The USVI government is the single largest WAPA electricity customer, accounting for approximately 15-20% of annual electricity demand. Other large industrial customers include tourist hotels, large retail facilities (e.g., shopping malls), and the industrial plants. However, other large energy consumers are off-grid. Approximately 10-15 of the top electric power loads in USVI are operating off-grid and/or with net metering sending electricity back to the grid (e.g., The Buccaneer Hotel on STX; see Figure 17). Even though some of these larger customers are grid connected, they have decided not to rely on WAPA for electricity needs because of the high cost and/or lack of reliability. For example, the Diageo Distillery on STX has 100% underground electrical lines feeding it directly from the local substation but still decided to invest in its own generation.

Only customers with the financial resources to invest in their own generation can afford to move off-grid (e.g., large vacation resorts). Their departure creates the potential for an economic ‘death spiral’ (Felder and Athawale 2014) in which residential customers who remain on the grid carry an increasing burden of the same fixed and variable costs for grid operations spread over a decreasing customer base. The only way for WAPA to recover these costs is requiring higher electricity prices for system operation. With the decreasing cost of renewable solutions and an expanding range of solution providers, this in turn incentivizes more customers to invest in going off grid, exacerbating the problem.

Figure 17. The Buccaneer Hotel operates independently from WAPA using their own diesel power generation site that reportedly maintained electrical power throughout Hurricane Maria. Photo: NPS, March 2018.

The large number of grid-tied customers with distributed generation is both a benefit and problem for WAPA operations. The largest share of renewable energy generation across the USVI is due to distributed solar PV and wind systems. WAPA has a net metering program that allows these customers to sell electricity back to the grid. WAPA uses these sales to both offset the need for fossil fuel generation and to increase their renewable energy generation portfolio to meet the 60% fossil fuel reduction goal by 2025. However, WAPA is unable to control the output from these distributed assets and lack a feed-in-tariff program to manage their variable costs. Since net metering sells electricity back to the grid for the same price as electricity generated at power plants, they do not help mitigate variable fuel or operational costs incurred by WAPA. In addition, customer reliance on solar PV without backup battery supply increases operational difficulties with feeder voltage regulation and tap changing transformers on distribution circuits.



(A) (B)

Figure 18. (A): Typical daily load profile for a feeder power line in STT serving commercial and industrial customers. (B): Typical daily load profile for a feeder power line in STX serving residential customers. *Note:* scale different for each sub-figure. Reproduced from: Burman et al. (2011).

2.3.4 Electric Loads and Critical Services.

Typical electric load profiles in USVI power systems fall into two categories: commercial/industrial and residential (see Figure 18). Depending on the location of a WAPA feeder, the customers served by the feeder are either residential or a mix of commercial and industrial customers. These two types of feeders experience differing load profiles that impact generator dispatch and electricity sales. A past study by NREL presented typical daily load profiles for these two different kinds of feeders (Burman et al. 2011) reproduced in Figure 18. Based on this study, a typical daily commercial/industrial load profile shows a sharp load swing in the morning when industrial equipment is turned on, relatively flat load

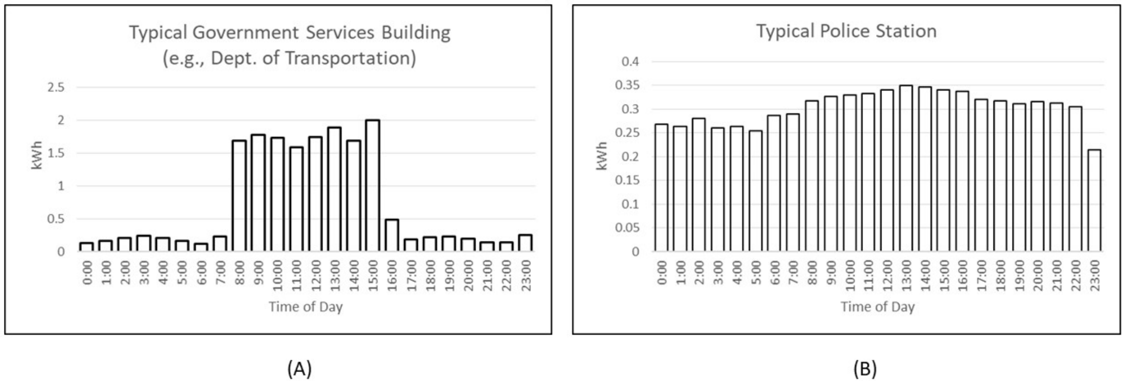


Figure 19. (A): Typical daily load profile for a USVI Territorial government building. (B): Typical daily load profile for USVI Police Station. *Note:* scale different for each sub-figure. Data provided via Personal Communication (2018).

throughout the day, and another swing at the end of the work day as equipment is turned off. In contrast, a typical daily residential load profile for a feeder with a high load factor experiences three peaks in the early morning, afternoon, and evening with minimum load in the late night.

Many infrastructure systems that provide critical services to the Territory require electricity to operate, including water facilities, transportation infrastructure (e.g., ports), first responders (e.g., police stations), healthcare facilities, and food supplies among others. Understanding the needs for these loads is important for ensuring resilient operations of electric power and other critical systems during emergencies. Some critical loads in USVI power systems have similar demand patterns to commercial / industrial and residential customers (Figure 19). Specifically, Territorial government service buildings (e.g., the Department of Transportation Offices) have loads similar to commercial / industrial customers, where police stations and schools have loads similar to residential customers.

In contrast, other critical loads have unique load profiles unlike typical customers (Figure 20). For example, ports have similar load profiles to commercial / industrial customers, but require higher loading at night rather than during the day. Hospitals have similar

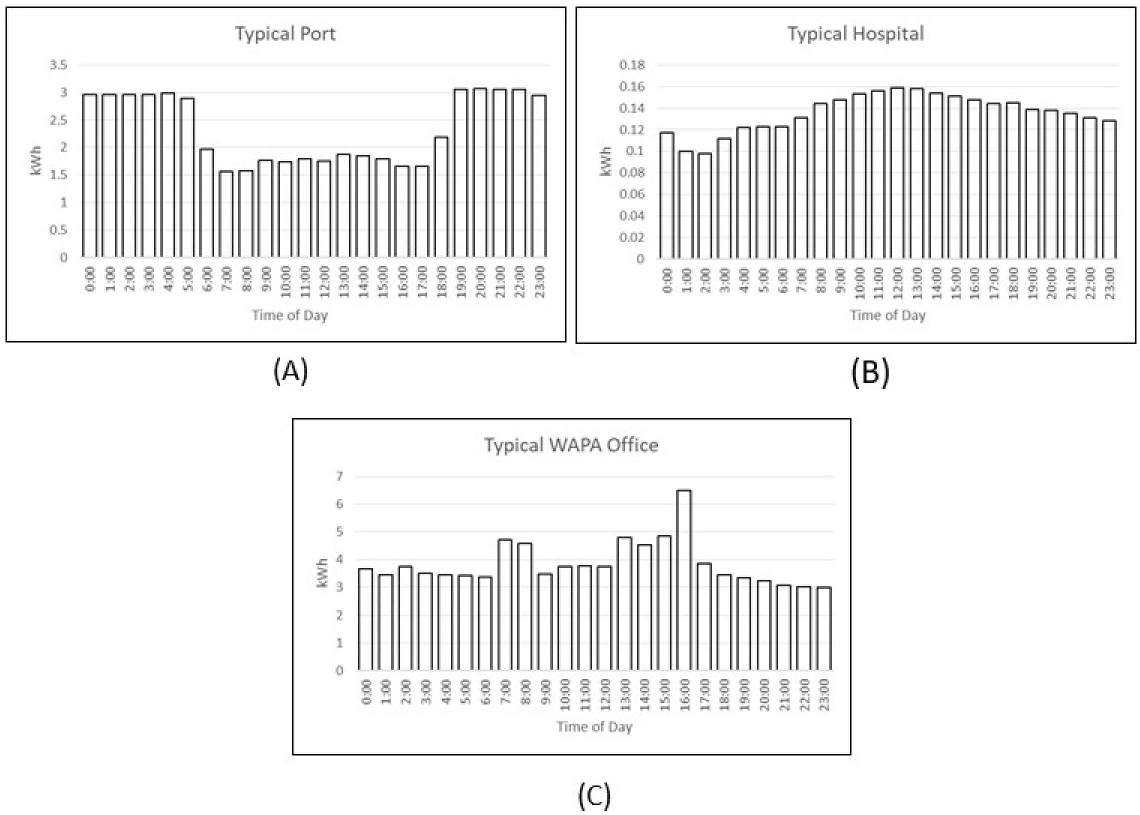


Figure 20. (A): Typical daily load profile for a USVI Port. (B): Typical daily load profile for USVI Hospital. (C) Typical daily load profile for a WAPA infrastructure office *Note:* scale different for each sub-figure; Hospital data from 2017. Data provided via Personal Communication (2018).

load profiles to residential customers, but with large variation in power demand of nearly 50% throughout the day. Finally, some loads for WAPA facilities show significant swings in demand throughout the day. Policies designed to improve power grid resilience of broader communities might promote technologies or system designs that do not serve these loads. For example, a renewable energy system designed for average commercial/industrial customers may not generate electricity during the night when ports need it the most. Consideration of these unique load profiles is especially important during crises when these critical facilities must be available.

2.4 Hurricane Impacts and Mitigation Efforts

Hurricanes Irrma and Maria caused significant damage to electric power infrastructure across the USVI. Detailed explanation of the events during the storms and afterward to recover failed infrastructure is well-documented by the USVI Hurricane Recovery and Resilience Task Force (2018).

Here, we focus on capturing current activities to harden and improve STT/STJ and STX power systems. Of the $7.5 billion in post-storm disaster funding, a projected $850 million will go toward building a more resilient electrical grid (Clark et al. 2018). The devastation of the hurricanes revealed failed systems and revealed infrastructure vulnerabilities not previously known in normal operations. Associated infrastructure installations and upgrades to remedy these problems will have a rapid and profound effect on the operational resilience of WAPA's power systems. However, most upgrades are focused on preventing another catastrophic storm from destoying STT/STJ and STX power systems. The current lack of systemic guidance and/or consideration of established power system tensions may inhibit the success of these projects.

Figure 21. Downed and damaged power/telecommunications lines across the territory as a result of Hurricanes Irma and Maria. (Left) Damaged Power Lines STT. Photo: VI Consortium (Right) Damaged Power Lines Charlotte Amalie. Photo: Samoa Observer.

Figure 22. WAPA employees replace a blown underground transformer in downtown Christiansted. This outage lasted approximately 24 hours, affected numerous businesses and residents and, according to the repairmen, was the result of a faulty transformer. Photo: NPS, March 2018.

2.4.1 Power System Vulnerabilities Revealed by Irma and Maria.

During normal operations, WAPA's reliability issues are tied to generation; however, during severe weather incidents, transmission and distribution infrastructure often becomes the point of failure.

As a result of both hurricanes, nearly 100% of electricity customers lost electricity and the electrical transmission and distribution networks in the Territory were significantly damaged: 60% on STX, 80% on STT, and 90% on STJ (Figure 21). According to FEMA's 098 News Release, WAPA restored electricity to 100% of eligible customers across the territory by January 2018 (Federal Emergency Management Agency 2018b).

Not surprisingly, the system remains in a vulnerable and fragile state as it recovers. During January and February 2018, STT experienced three additional large-scale outages (e.g.,

Figure 22). However, there are a variety of efforts underway to create a more reliable grid.

2.4.2 Post-Hurricane Upgrade and Hardening Activities.

More Flexible, and Redundant Generation. WAPA seeks to increase generation redundancy and flexibility through the use of two generation sites and a larger number of smaller generators, per island—a solution currently underway as part of WAPA's long-term recovery efforts.. This will reduce the vulnerability from a potential single point of failure while increasing the flexibility of generation for fluctuations in the island's loads. It also creates more flexibility, because an increased number of smaller supplemental generator turbines allows the performance of the generation plants to be more finely tuned and ensure the generators are operating in their optimal performance range.

Underground Lines and Composite Poles. Under the recovery efforts, WAPA is expanding its efforts to bury additional electric lines underground, which began approximately 20 years ago (Bryan and Burton 2017). Additionally, WAPA is installing composite poles that can sustain higher wind speeds than traditional wooded poles following the 2017 hurricanes. WAPA has installed pad-mounted and underground transformers (replacing pole mounted transformers). Current projects are projected to benefit approximately 41% of electrical customers in the USVI. The projected cost for this project is $303 million dollars (Bryan and Burton 2017), but the current status, actual cost, and projected timeline are still in development. A full breakdown of project associated with the territory 404/406 mitigation plan are can be found in Federal Emergency Management Agency (2018a).

Additional Interconnectivity. Another potential way to mitigate the volatility of the small grid in the USVI is to connect it to a larger system where the overall load is more stable. To this end, there has been discussion of interconnecting power systems across local islands. These discussions include underwater DC interconnections between Puerto Rico and STT, Puerto Rico and STX, STT/STJ and STX, and STJ and the British Virgin Islands. Such interconnections are deemed technologically feasible across several reports (Bioimpact Inc. 2011; Clark et al. 2018; Gevorgian 2011; Anderson et al. 2011), however, lack of available funding remains a barrier to support each project.

3 USVI Water Systems

There are three distinct categories of water that are relevant to Virgin Islanders: stormwater, potable water, and wastewater. We consider the infrastructure systems for each in turn.

3.1 Stormwater Management

Each island in the territory is divided into a number of watershed drainage basins (or simply watersheds), defined as an area of land that captures rainwater which then flows and drains into a common coastal outlet. The flow of water in a watershed is governed by natural watercourses (also called “guts” or “ghuts”) that collect and channel the water as it makes its way to the ocean (Gardner et al. 2008); see Figure 23. As noted by the USVI Department of Planning and Natural Resources (2016), “There are no large freshwater lakes or ponds, and no perennial streams on any of the islands; intermittent streams can only be seen after heavy rainfall or during the rainy season (May-November). The absence of large freshwater resources and perennial streams means that guts (watercourses) form the basis for watershed management in the territory.”

3.1.1 System Concerns

There are two primary concerns regarding watershed drainage. First, periods of heavy rain generate large stormwater flows that can cause flooding, threaten lives, and/or damage property and infrastructure (see Figure 24). There is a long history of such events. For example, portions of St. Croix flooded on October 8, 1977 when a tropical storm dropped nearly 16 inches of precipitation (U.S. Geological Survey 1977). Although changes in global weather patterns have recently *reduced* the overall annual rainfall in the Caribbean (Environmental Protection Agency 2016), the USVI still experiences intense periods of rain during storms. Appendix A of NOAA Coral Reef Conservation Program (2014) lists 24-hour rainfall magntiudes, with the 50-year and 100-year rainfalls ranging 11.8-16.6 inches and 13.9-19.8 inches, respectively.

The second concern is environmental. Rainwater runoff can carry soil, pollutants, as well as other hazardous materials. Because the coastal waters and marine life that surround the USVI are vital to the health and economy of the territory, the management of runoff within the watersheds is important for combating environmental threats of erosion, sedimentation,

Figure 23. An uphill view of a drainage culvert and a 'Gut' line. Photo: NPS, June 2018

and pollution, especially for coral reefs (Catanzaro et al. 2002; NOAA Coral Reef Conservation Program 2014). Scientific guidance for environmental planning and protection dates back to at least 1976 (Wright et al. 2002; Noori and Taylor 2011). However, increased land development over the last several decades—in the absence of a land use plan, as well as a lack of environmental or planning regulation enforcement—has increased these runoff effects (for a history of land use planning in the U.S. Virgin Islands, see Division of Environmental Protection 2004). The USVI Department of Planning & Natural Resources (DPNR) is the government agency responsible for environmental protection issues, with additional federal oversight from the Environmental Protection Agency (EPA); see Environmental Protection Agency (2018a).

The USVI Department of Public Works (DPW) is responsible for the maintenance of the guts throughout the island, in conjunction with road development, built drainage, and other flood management. However, the USVI Department of Planning and Natural Resources (DPNR)

Figure 24. Left: Rainfall in March 2018 causing downhill soil erosion and heavy street flooding north of Christiansted, St. Croix. Right: A washed out road from heavy rains from Hurricane Irma reduces traffic to one lane in the hills above Charlotte Amalie, St. Thomas. Photos: NPS, 2018.

also shares responsibility for stormwater management through its planning, permitting and regulatory functions.

3.1.2 Hurricane Impacts

The heavy rains and extreme winds during the 2017 hurricanes resulted in considerable water and debris in the guts, which in turn led to considerable damage to culverts, roads, pipes, and other infrastructure systems. These are detailed in the relevant section for each.

3.2 Potable Water Systems

Because the USVI has few natural fresh water resources other than rainwater, Virgin Islanders have historically relied on residential and commercial cisterns that collect and store rainwater for use. More recently, portions of the territory rely on a potable water distribution system owned and operated by WAPA (Figure 25), with additional service for the territory provided by a number of private water hauling companies that deliver fresh water by truck. Currently, WAPA is responsible for the production of desalinated potable water to approximately 12,500 to 13,000 customers across STT, STX, and STJ (about 10,500 residential and 1,500 commercial). This section provides an overview of this water infrastructure and outlines some of the key challenges facing it.

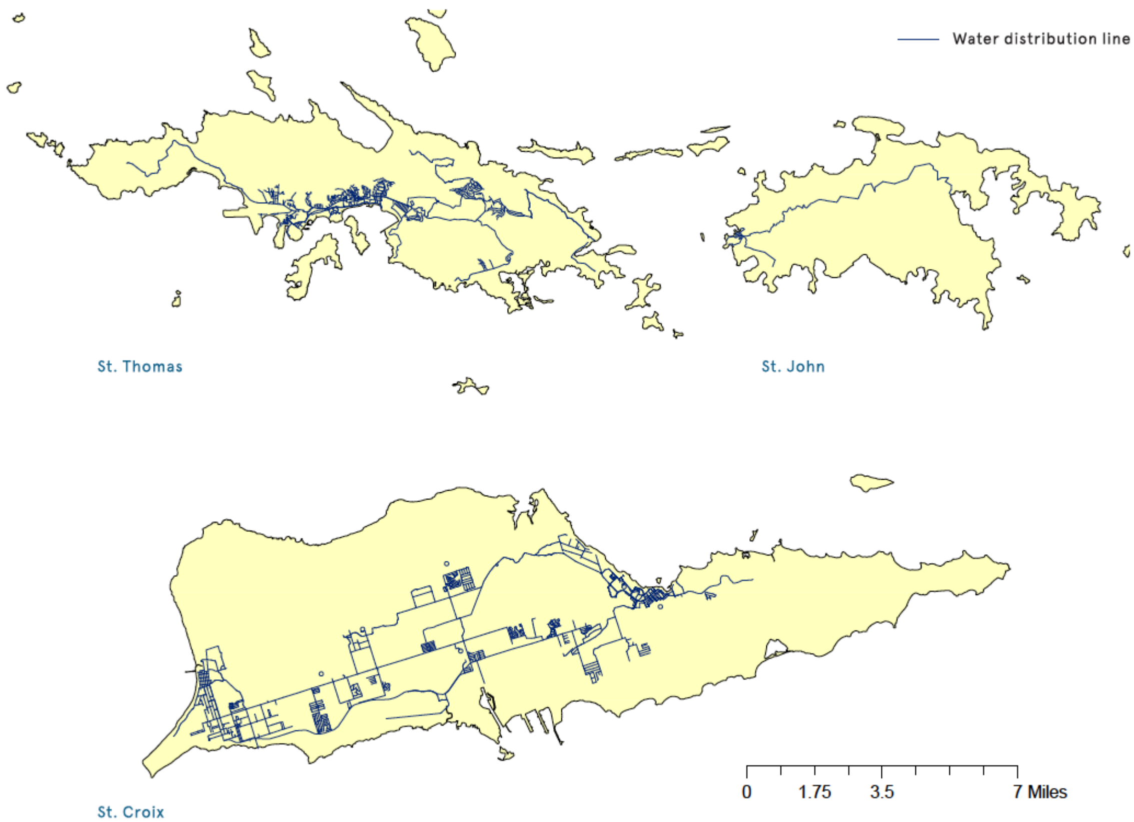


Figure 25. WAPA potable water distribution network, as reported on p. 115 of USVI Hurricane Recovery and Resilience Task Force (2018).

3.2.1 General Features

There are several features that are common across the entire territory.

Customer Demand. Around 40 to 45% of the population has access to the potable water distribution system provided by WAPA (about 30% use it as their primary source while the other 70% use it as a back up to their cisterns), mostly in the low-lying population centers (there is limited pumping of water to uphill areas). Hospitals, schools, and government buildings are primary WAPA water customers. Cisterns used to be required for all buildings, but this is no longer the case if there is access to the WAPA distribution system. Cisterns are mostly subterranean, but above-ground tanks are also used for water storage.

Rainfall. During a normal year, weather is characterized by a dry season (December-June) and a wet season (July-November). The mean annual precipitation for different parts of the territory ranges between 36-53 inches, with the average storm depth less than one inch (NOAA Coral Reef Conservation Program 2014). As noted by the Environmental Protection Agency (2016):

> "Although heavy rainstorms have become more common, shifting weather patterns have caused total rainfall to decrease in the Caribbean region. Total rainfall is likely to continue to decrease, especially during spring and summer. Warmer temperatures also reduce the amount of water available because they increase the rate at which water evaporates (or transpires) into the air from soils, plants, and surface waters. With less rain and drier soils, the U.S. Virgin Islands may face an increased risk of drought, which in turn can affect water supplies, agriculture, and the economy."

A drought in 2015 caused farmers to lose crops and livestock, resulting in a disaster declaration by the U.S. Department of Agriculture (Virgin Islands Consortium 2015).

Production. Because there are few year-round natural sources of fresh water, the USVI needs to produce additional water. Historically, WAPA used desalination units that relied on steam from boilers to generate clean water, but began replacing them with more energy efficient reverse osmosis (RO) units in 2008, completing the transition in 2013. We provide additional details below.

Pumping. Although much of the potable water flow in the territory is fed by gravity, WAPA requires pumping stations to lift water over elevated areas, as well as to maintain pressure. These pumping stations are powered primarily by the WAPA electric grid, and there is limited backup power from generators. Extended power outages can cause ripple effects in the availability of potable water.

Piping. Water distribution is provided by a piping system that was installed in phases between the 1930s-1970s and is now well beyond its life expectancy. Although water quality issues (e.g., discolored water) have been reported as a result of pipe corrosion and a lack of circulation in some areas (i.e., turbidity), there have been no known health effects reported by the EPA. Another consequence of the old water distribution system is suspected high water loss due to leaks in the system.

Metering. Metering for WAPA water is a mix of individual metering (at the level of an individual building) and master metering (one meter for a community that a local housing authority manages for billing). Metering technology is also a mixture of analog systems that require in-person physical meter recording and Automatic Metering Recording (AMR) infrastructure that allows for drive-by recording (about 30% deployed as of May 2018). Although AMR creates the potential for disruption from technological failure or deliberate hacking, it is less vulnerable to cyber-attack than traditional advanced metering infrastructure with two-way data communication and the first-order efficiency gains from this automation are undeniable.

3.2.2 Potable Water Infrastructure on STT/STJ

The islands of STT and STJ share a single potable water system owned and operated by WAPA. Water production is outsourced from WAPA to Seven Seas Water Company (established in 1996), who operates a facility co-located at the Randolph Harley power plant just south of Cyril King Airport on Krum Bay. This facility currently has a Sea Water RO unit with a maximum capacity of 3.3 million gallons per day (MGD) and an Ultra Pure Water system with a maximum capacity of 575 thousand gallons per day (0.575 MGD). Demand for STT and STJ is a combined 2.2-2.7 MGD. WAPA operates the facility at maximum production rates only intermittently because making water at maximum capacity for long periods creates maintenance issues.

STT has onsite water storage of 35 million gallons (MG), located at the main pump station at Sarah Hill (adjacent to the production facility; see Figure 26). Primary storage comes from three storage tanks, each with 10.5 MG capacity. (There used to be four tanks total, but two tanks were damaged in a 1995 hurricane, and only one was repaired.) These tanks are connected in serial and can feed from one into another via gravity; all of them can gravity feed into the pump station. Two of the tanks have protective rings to maintain integrity

Figure 26. Some of WAPA's Sarah Hill Water storage tanks (green tanks) seen in the distance, just behind the Harley Power Plant on St. Thomas. Photo: Tammy Swart, 2017.

in a storm, while the other does not. In preparation for a storm, WAPA will fill the tanks to protect them against wind damage (and it is good practice to top off storage prior to a potentially disruptive event).

WAPA performs considerable treatment to the water, some at the plant and during the pumping. This includes the addition of chlorine, which is produced on site thus reducing the need to store large amounts of the chemical.

Potable water leaves the primary pump station at Sarah Hill using a 24-inch main pipe. From this main pipe, water is moved across the island in three ways. From Sarah Hill pump station, water is split to the western side of the island, ending at the University of the Virgin Islands (UVI) campus via a 10-inch pipe. For Charlotte Amalie and surrounding areas, an 18-inch main splits and runs along Veterans Drive distributing water using three, 10-inch T-connection points. Booster pumps move water from the main to higher elevation areas. Water for cruise ships is sent using the same pipe along Veterans Drive to West Indian Company (WICO) for storage in large cisterns. WAPA sends water almost continuously to WICO, and the cruise ships draw their water from these cisterns. Finally, the 24-inch pipe moves water to the Donoe pumping station, the second major pumping station on the island located near the hospital.

The Donoe pump station pushes water at 280 pounds per square inch (psi) to lift the water over a 600-foot elevation hill to feed a 5.5 MG tank (located at 580 feet elevation). The Donoe water tank then uses a gravity system to service two groups of customers. First, the tank is used to service a limited number of customers on the eastern side of STT. Second, the tank feeds all WAPA customers on STJ via an underwater pipeline from Red Hook to Cruz Bay. Notably, the Donoe water tank can feed the downstream system via gravity alone for five days, assuming it is filled to capacity. WAPA is currently installing a first booster pump station on the east side of STT to provide additional service to customers in the hills.

The island of STJ is connected to WAPA potable water infrastructure via a single 6-inch underwater pipe that has a capacity of approximately 1.5 MGD. WAPA reports a daily demand on STJ of 0.10-0.15 MGD, excluding hotel demand. All major hotels on STJ are reported to have their own generation and RO units, with connections to the system coming primarily from smaller bed-and-breakfast establishments, businesses, and residences (cisterns are used heavily here as well). However, the hotels maintain a connection to WAPA for backup and can draw an additional 0.2 MGD of demand when using the WAPA system. There is a single pump station located at Cruz Bay on STJ which is exclusively a local distribution pump. There are two elevated storage tanks (0.75 MG and 0.5 MG) and one distribution tank (0.132 MG) on STJ. If demand exceeds the pumping capacity of the distribution station, then additional water is gravity fed from the storage tanks; these tanks are elevated but not enough to feed the system entirely via gravity. There is an older 'weak pipe' (capable of supporting only less than 30 psi) that can be used only in the absence of pumping, which is rare. The pump station has two primary pumps and one spare, and the station has its own generator for power backup. Overall, STJ maintains approximately 10 days of water supply without hotel demand, and only 3-4 days of supply if the hotels are on the system.

Cisterns and Water Haulers. The majority of STT (approximately 80%) uses cisterns for water collection and use. In particular, the area on STT east of the hospital uses cisterns primarily, with WAPA as backup only. Of those on cisterns, it is reported that only 30% buy water and are serviced by water haulers. There are 10-20 water hauler companies on STT who get their water primarily from less expensive wells in rural areas. Wells in the western part of STT are also used to produce bottled water. Water haulers typically purchase water from WAPA only when the wells run dry, both because of convenience (i.e., the wells are close to customers in rural areas) and lower cost. In general, water from haulers on STT costs approximately twice that provided by WAPA.

There is much greater reliance on water haulers on STJ, particularly for the east side of the island. Currently, STJ has 5-10 water hauler companies. At one point recently, there was a proposal for WAPA to install a RO water production facility at Coral Bay, but this did not receive local approval due to concerns that it would result in excessive population growth. There exists the potential for WAPA to put an underground pipe to support the east side of STJ, and there is also the potential for a secondary underground pipe from STT to STJ.

Design and Modernization. The pump station at Sarah Hill was inherited by WAPA from Public Works in the 1990s and in general is oversized for the current distribution system. In addition, in many locations the pumps are poorly placed (e.g., requiring a pressure-reducing valve only later to re-boost pressure in the system). As a result, there is lots of pressure-reducing, pressure-maintaining, and/or pressure-relief infrastructure throughout the system in order to keep the downstream pressure at the 80 psi required to make things work. WAPA has a plan to modernize these pumps, but will only implement it once the current system fails. The average age of piping infrastructure is reported to be 30 years, with some older pipes (70-80 years old) in town. In rural areas, many pipes were installed in the 1970s but not connected to the main system until the 1990s, making their 'service age' less than their 'installation age.'

The potable water infrastructure on STT and STJ experiences line loss consistent with industry standards (around 10%) with redistricting being credited for their management. Service coverage has historically not been a primary concern on STT because the system of cisterns and water haulers is functional. A bigger issue is public perception of water quality. Thus, WAPA has been focusing on improving existing infrastructure over expansion. WAPA currently has only a few outstanding projects to fix really bad areas for distribution, then plans to focus on rehabilitation of its storage tanks.

All three main water pumping stations that service STT and STJ (Sarah Hill, Donoe, and Cruz Bay Pump Station) are currently operated manually. A grant is in place to convert all stations to an automated Supervisory Control and Data Acquisition (SCADA) system in FY18, however, the project will continue into FY19 with completion scheduled for 2020 across the Territory. Pump stations on STT do not currently have any backup generators and are completely dependent on WAPA for power. However, following the 2017 hurricanes, WAPA has submitted paperwork for grants to acquire generators at these stations.

As a general storage plan for potable water, WAPA maintains its tanks at approximately 60% capacity during the winter and 80% capacity during the summer. In case of a hurricane, it will fill its tanks during 4-5 days prior to the event.

3.2.3 Potable Water Infrastructure on STX

The potable water system on STX is owned and operated by WAPA and similar to the system on STT/STJ in several ways. There is a single water production facility co-located at the Richmond electric power plant that uses RO to produce its water. As in STT, this facility is owned and operated via contract for WAPA by Seven Seas Water Company. The facility on STX has two RO systems with 1.5 MGD and 2.2 MGD capacity respectively. The arrangement with WAPA specifies that Seven Seas maintain the ability for a 25% increase in production capacity when necessary. The daily demand for potable water in the system is approximately 2.7-3.0 MGD.

However, this is where the similarities end between the STT and STX water systems. On STX, the vast majority of customers on the island—approximately 70%—rely on the potable water system. However, the distribution does not cover 100% of the island. Many houses have cisterns, but these are effective only during the rainy season. In places where the water lines do not exist, customers rely on water haulers to supplement rainfall.

Potable water for STX is fed from a single 10.5 MG storage tank located at the Richmond plant. There are three pumps with a combined capacity to push 2.0 MGD (the production capacity at Richmond is 3.0 MGD). These pumps use variable speed motors to control pressure. Pumped water leaves the Richmond facility via two main water lines that feed two outlaying pump stations: Concordia station to the north and Contentment station to the south. The system currently does not reach the eastern end of the island. The Concordia north station has two pumps, one in operation and one in reserve. Water pumped through Concordia comes down hill and, similar to the STT system, uses boost pumps to move water to higher elevation areas. The Contentment south station utilizes two pumps running simultaneously.

Water storage on STX is spread across the island in several tanks: Mon Bijou (2 MG), Mountain (5 MG), Kingshill (5 MG), Recovery (1 MG), Anna's Hope (0.1 MG), Grover Place (0.1 MG), and New Street (0.1 MG; but currently out of service). Collectively, the system has 22 MG of storage capacity; this equates to approximately seven days of storage for the population.

Water from these storage tanks moves to the rest of the system via a combination of gravity-fed lines and pumping. There are several service and pumping stations around the island—many dating back to its original construction in the 1960s—necessary to maintain system pressure. All of these pumping stations are manually operated and solely dependent on the WAPA electric grid, currently with no backup generator capacity. System monitoring is implicit from daily testing of water quality and pressure at each station.

Water Losses. The potable water system on STX is reported to suffer from considerable water losses, in some cases as much as 40 MG of unaccounted water per month. The backbone of the system is from the 1960s and has not been updated to keep up with population growth. However, it is unclear whether these reported water losses are real or an artifact of theft and/or inaccurate accounting. In the early days of the system, water on STX was free, then later meters were installed for billing purposes. Some customers never received a meter (i.e., were 'grandfathered' in the system), and their use is not officially recorded. In addition, many of the meters in the system are old and believed to be under-reporting their actual use; this gives rise to the appearance of water loss. Anecdotally, when select meters were replaced in high-loss areas, these losses nearly disappeared. A line loss audit was contracted and conducted for STX that recommended redistricting, line loss surveys, and AMI deployment to better manage line loss in the future.

Water Haulers and Competition. As on STT and STJ, private water haulers are used by consumers on STX who do not have a direct connection to the WAPA water distribution system. In contrast, however, water haulers on STX directly compete with WAPA both in terms of production and distribution. At the Richmond water plant, WAPA has a fill stand pipe to sell water to water haulers. However, as RO production units have become more affordable, several private companies (e.g., Plaza Extra grocery) have installed their own production systems; these producers often sell water at a lower price than WAPA. Thus, as the barriers to entry for water production and distribution become lower, WAPA is facing a considerable threat from competitors who do not have to support the fixed cost of storage and distribution infrastructure.

Other factors adversely affect WAPA's ability to compete for water. Many of its biggest customers, including the local government, schools, and hospital, are significantly behind in their payments. Whereas water haulers do not require payment until 30 days after delivery, WAPA now requires pre-payment for water. As of June 2018, two of the largest water haulers on STX have plans to build their own RO systems. There is considerable concern that the loss of these and other customers from WAPA could exacerbate its financial troubles.

3.2.4 Hurricane Impacts

Increased rainfall from storm events creates several issues for potable water systems. Some consumers believe in capturing water during the storm, and this can reduce the need for potable water purchases during rainy seasons. However, rainwater that flows into cisterns can contain a lot of salt. Moreover, excess water from rain can also result in overflow that lifts the top of a cistern exposing it to the elements, so many people disconnect their capture system from their cistern prior to a storm.

After a major storm, there tends to be a major increase in potable water use for purposes of cleanup. Moreover, most cistern pumps are powered by electricity, and the loss of power often means that people cannot access water from their cistern except by manual means (e.g., bucket and rope, siphon hose). Customers often need backup generators to pump water in addition to electricity.

Overall, WAPA's water production and distribution systems survived the 2017 hurricanes much better than their electricity counterparts. There was little damage to water production or pumping facilities on either STT or STX. Some water tanks experienced damage from the storms but nothing substantial was reported other than some roof damage. Chlorine was stockpiled before the storm, as its rapid depletion was a concern.

A primary problem for the water system was the loss of electric power across the Territory. When electricity infrastructure failed, the system was entirely dependent on backup generators for pumps. These operated well initially but were limited by the fuel supply; FEMA provided the bulk of emergency fuel to keep pumps running. Moreover, after three months of continuous use, these generators started to break down. Some pumps providing flow to distribution on STT and STX needed new generators, however, logistical problems made it difficult to obtain spares; in some cases it took between four to six weeks to obtain them. Seven Seas relied on above ground power lines at STT to provide electricity to their production facilities. Consequently, production had no power for 10 days. During this time, pressure out of the Sarah Hill tanks was maintained using generators to power the pumps. However, because the vast majority of the electric transmission and distribution system was down for a considerable period of time, the lack of power at the remote pumping stations compromised the ability to maintain water pressure to outlying areas. It took 14 days to restore power to the Donoe pumping station. WAPA implemented water rationing after two days to slow demand. However, the Donoe storage tank ran down to a height of approximate 3 feet (about 6 hours until dry) when power to the pumping station was restored. WAPA is currently looking to buy a fuel truck that can deliver fuel to generator units to prevent this near miss in the future.

STX also suffered issues from lack of electricity at pump stations. These stations are ordinarily powered by the WAPA electrical grid. Only three out of the 18 stations across the islands had backup generators. Three days after the hurricane, WAPA was able to borrow a generator from a local contractor hooked up to the Contentment pump station to get water to Fredericksted (Augustin 2018). It took around two weeks for the STX pumping stations to get back online. STX's major challenge was getting water to mid-island and west-island areas where issues were exacerbated by uprooted trees breaking water lines that fed storage tanks in the area. Storage tanks were eventually depleted and these areas had to rely on water trucks to provide water until the distribution network was repaired and operational again.

WAPA has since identified the needed generators (two 100KV, 3-phase generators per pump site) and are waiting on delivery for installation. In addition to a lack of backup electrical generation, the water system valves on STX require upgrading as they are primarily pressure reducing and are manually operated. In many cases, the system experiences failed valves that are stuck in position or cannot close, and locating these valves can be a challenge: some are either missing or are covered and inaccessible (e.g., paved or built over).

The potable water infrastructure on STJ remained operational after the storm with tanks and pumps suffering minimal damage. The main concern was maintaining fuel for generators at the main pumping station and maintaining communications with the WAPA water crews on island. Disruptions to fiber telecommunication and ferry service to the island caused WAPA water officials to rely on FEMA resources in order to communicate and coordinate the STJ recovery effort.

3.3 Wastewater Management

The Virgin Islands has two methods of wastewater disposal: septic systems and sewer lines.

Septic systems are stand-alone systems that provide ‘primary treatment’ of wastewater in a ‘septic tank’ (i.e., to settle out solids and float oils and greases in the waste stream) before the wastewater flow (also called effluent) drains by gravity into subsurface trenches or a piping network for secondary treatment (see Parten 2009, for an introduction). Septic systems require routine maintenance and are typically pumped every three-to-five years (Environmental Protection Agency 2018b).

The Virgin Islands Waste Management Authority (VIWMA) is a semi-autonomous agency that is “mandated to operate and maintain the wastewater and solid waste infrastructure throughout the Territory” (Virgin Islands Waste Management Authority 2018a). The VIWMA is led by an executive director who oversees the day-to-day operation, and it also has a seven-member board which sets policy for the organization. Here, we consider the operation of wastewater and its interaction with other water infrastructure systems.

The Wastewater Division of VIWMA “provides wastewater services including collection, pumping, treatment and disposal to approximately 60% of the Virgin Islands 115,000 residents. Everyday, more than 4.5 million gallons of wastewater rushes through those pipes, heading toward the wastewater treatment plants on St. Croix, St. Thomas and St. John” (Virgin Islands Waste Management Authority 2018d).

Movement of wastewater is primarily gravity-fed with the use of pumping (or ‘lift’) stations to move wastewater uphill and also tanks that provide temporary storage. According to VIWMA, the system currently consists of 8 treatment plants and 31 pump stations across the territory, arranged as “a large network of underground pipes and pump stations that transport wastewater to the treatment plants and the ocean discharge of treated effluent" (Virgin Islands Waste Management Authority 2018d). According to the VI Law, anyone located within 60 feet of a public sewer line is required to connect to the system.

The wastewater system in the USVI is often co-located with the watershed drainage guts used for managing stormwater. In many locations, the wastewater system has combined sewers, with wastewater and rainwater moving together. Whereas wastewater is managed by VIWMA, maintenance of the guts belongs to DPW and DPNR.

Funding for the operations and maintenance of the Territory's wastewater collection, treatment and disposal systems and facilities is not billed based on usage but is instead assessed on all property owners, residential and commercial, as an annual fee that is billed on the property owner's tax statement.

3.3.1 System Overview

VIWMA operates six of its WWT facilities on its own, but contracts the operation of two facilities—the Anguilla wastewater treatment plant on STX and the Red Point wastewater treatment plant on STT—to Veolia Group, a multi-national corporation based in France (Veolia Group 2018). As with other infrastructure systems, each island has its own characteristics.

STX. Only about 30% of the population on STX is served by the VIWMA sewage network—primarily in the areas surrounding Christiansted and Fredericksted, see Figure 27—with the other 70% using septic systems. There is a single public Waste Water Treatment (WWT) facility on St. Croix, the Anguilla WWT plant located near the airport. This facility was designed, constructed, and operated for VIWMA by contract from Veolia Water Solutions & Technologies Company (Veolia Water S&T). The Anguilla WWT plant can process 4 MGD and has the ability to use the effluent for agricultural purposes (Water Design-Build Council 2018). Electricity at this facility comes from WAPA. Generators are the primary source for on-site electrical needs in the event of an emergency. Movement of wastewater to the Anguilla WWT is supported by 15 pumping stations located throughout the island. Industrial facilities, such as Cruzan Rum and Diageo Distillery, operate their own industrial wastewater treatment facilities.

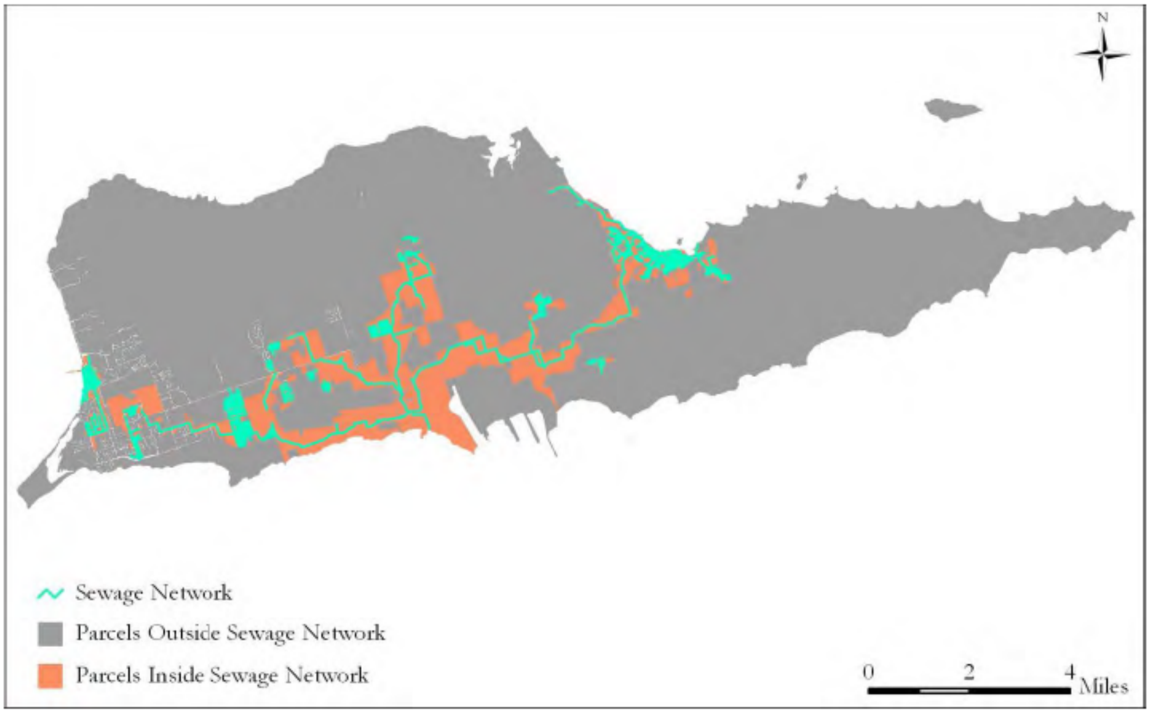


Figure 27. Depiction of St. Croix sanitary sewage network as of 2011 (Source: The Cadmus Group, Inc. 2011, originally as Figure 1-6).

STT. Whereas the wastewater system on STX is an integrated network that collectively feeds a single WWT facility (also called a 'WWT Plant' or WWTP), the system on STT is a collection of disparate systems that serve different parts of the island. The area surrounding Charlotte Amalie is the largest service area, with six different pumping stations collectively feeding the Red Point WWTP (officially called the Pedrito A. François WWTP). This facility was also designed, constructed, and operated by Veolia Water S&T, and it also boasts a design to support an average daily flow of 4 MGD with a peak hourly flow of 12 MGD (Water Design-Build Council 2018). The Mangrove Lagoon WWTP serves the southeastern portion of STT and is fed by three pump stations. Local treatment at Red Hook in the eastern part of STT is provided by the Vessup WWTP. The island is also served locally by the Brassview WWTP in the north and the Bordeaux WWTP in the west (Figure 28).

STJ. Wastewater infrastructure on STJ is oversized for its current population because planned development never materialized. There are three WWTPs: the Cruz Bay WWTP in the west part of the island is fed by three pumping stations, the George Simmonds WWTP in


Figure 28. Bordeaux WWTP on the western side of STT. Source: Fluence Corporation (2018).

the center of the island is fed by a single pumping station, and the Calabash Boom WWTP in the east is fed by two pumping stations. The Cruz Bay WWTP operates 24 hours per day, but the others are used only intermittently. VIWMA is looking to reroute line or add a pumping station to bring more wastewater to the Cruz Bay facility.

3.3.2 System Challenges.

The wastewater management system faces a variety of challenges that existed prior to the 2017 hurricanes.

Incomplete System Knowledge. Like many infrastructure systems, the wastewater treatment system in the USVI is the result of ad hoc development over a long period of time, and it is challenged by "unmapped sewer lines, undocumented records of users and illegal connections, and years of neglect. It creates a unique challenge to overcome. The sewer system, which is more than 210 miles of line, consists of pipes made of ductile iron, bricks, and PVC piping, ranging in size from 4-inches to 48-inches " (Virgin Islands Waste Management Authority 2018d). This alone makes the system difficult to manage.

Stormwater Cross-Connections and Inflow. In some areas, stormwater drainage is cross-connected to the wastewater system, with wastewater mains running within or alongside the guts. Although intended to solve flooding issues, this puts an enormous burden on the lift stations and WWTPs, particularly during periods of heavy rain (e.g., hurricanes). The system also suffers from aging wastewater lines and poorly fitting manhole lids that allow stormwater and rainwater to enter the wastewater system, exacerbating the situation. In addition, debris from the stormwater system causes severe problems at pumping stations and also can clog the lateral drainage lines connecting to the storm and wastewater mains. The inflow of stormwater, the frequent failure of lines, and grease build-up can cause the system to become clogged and force sewage up onto the streets through manholes or result in untreated sewage flowing into the ocean. As noted in a September 12, 2018 press release (Virgin Islands Waste Management Authority 2018b):

> "Residents are advised that due to the expected inclement weather the sewer collection system may experience a large inflow of storm water into the system which may cause overflows in certain areas. The flow of rain water and storm water entering the sewer system may exceed the pumping capacity at various pump stations which pump sewage from residential and business systems to the wastewater treatment plants. After the rain and the storm water run-off subsides, the sewer collection system may continue to be impacted.
>
> Motorists are asked to use extreme caution when traversing through flooded roadways during and after the storm to avoid potential and known areas of manhole overflows. Residents are asked to avoid areas with standing waters. Persons with impacted immune systems are especially reminded to avoid all flood areas."

Design Issues. The design of the wastewater system is believed to be inadequate for the work it currently performs. As noted by O'Connor (2018), pumps at lift stations are not sized correctly for the burden placed on them during storm events and/or are not programmed to operate in an optimal manner. Moreover, "Some of the lift station pumps cannot be properly sequenced because the pressure created by operating more than one pump at a time will cause force mains to rupture" (O'Connor 2018). Pump stations have backup generators, but they require manual operation that can be slow to activate.

Aging Infrastructure and System disrepair. There is a general recognition that the wastewater system as a whole is in a serious state of disrepair which compromises its ongoing operation. Many of the sewage lines were badly weakened and/or damaged prior to the hurricanes. Some of the storage tanks are deteriorated to the point of near-failure.

Limited Monitoring and Control. The wastewater system does not currently have a SCADA system by which operators can monitor or control the operation of the system. In the absence of real-time monitoring and response, operational problems can quickly get out of control. Such emergency situations require rapid response by a Wastewater Division of VIWMA that is very limited in its resources.

Financial Challenges. The VIWMA faces extreme financial challenges that are the source of many of its problems. Its operating budget is paid out of a general fund collected from property taxes, rather than being payable based on use, and the government is reportedly providing only minimal funds. As of June 2018, the VIWMA is reportedly $15M in arrears in paying its contractors. For example, because of longstanding non-payment by VIWMA, Veiola has recently requested that the operation of its WWT facilities be transitioned back to VIWMA (Kossler 2018; Virgin Islands Waste Management Authority 2018c).

In addition, the current financial problems for VIWMA make it very difficult to get contractors to perform work, and these contractors require a premium because of the history of nonpayment. As a result, VIWMA only appears to be able to fix things that break, with little active management for operations and preventative maintenance. The common perception is that “everything is held together with band aids” and “nothing is really being fixed.”

3.3.3 Impact of Hurricanes

The 2017 hurricanes exacerbated the myriad issues with the wastewater management system in the USVI. Few, if any, of the backup generators at the pump stations operated, which resulted in uncontrolled sewer overflow for weeks. Once generators were installed, they did not hold up after months of constant use, and when they failed it was difficult to get spares.

The wastewater collection network on STT suffered perhaps the most damage. In three guts, sewer mains run under the floor of the concrete gut and the laterals are exposed pipe. The heavy flow and debris in the gut broke every exposed lateral, resulting in uncontrolled sewer flow until a bypass could be constructed (McPartlan 2018). Additionally, the manholes located in the guts were flooded and their lids displaced causing debris to enter and clog the system. Access roads to main lines and lift stations were impassable due to their deteriorated condition, making assessment and repair extremely slow. Many of these lines did not have replacement or bypass until March 2018; during this six-month period, raw sewage went into the guts, then into the bay. The Vessup WWTP was damaged and/or failed in a manner that it could not generate outflow, despite the uninterrupted inflow of waste; the only solution was to pump the incoming waste to another facility, which required considerable energy and was expensive.

In contrast, the WWT plants on STX an STJ fared relatively well in the storms. Outside of sewer line repairs, not too much restoration was needed there.

However, more than six months after the storms, many miles of sewer rights-of-way (ROW) had not been cleared or inspected, leading to concern that uprooted trees or displaced manhole lids could continue to cause uncontrolled overflows. Moreover, a lack of a comprehensive damage assessment has made it difficult to assess the overall need for repair; some FEMA officers have speculated that more than half of the existing sewer line will need to be replaced.

3.3.4 Mitigation Efforts

There are a number of mitigation efforts that can be implemented to increase the resiliency of the waste water systems in the USVI. These include: waste water debris mitigation for pumps, more resilient generators, redundant pumps, flood panels to protect systems, flood mitigation around pumping stations, moving WWT facilities away from the beach, moving vulnerable lines, and using concrete to reinforce lateral lines (Hanley 2018). However, all of these require resources—in terms of funding, equipment, materials, and people—that remain in short supply for VIWMA, DPW, and DPNR.

4 USVI Transportation Systems

The transportation sector of the USVI can be understood in terms of (1) the ports that connect the islands to each other and the outside world, and (2) the surface roads that support the movement of people and goods within each island. We consider each in turn.

4.1 Ports

Because of the USVI's remote location, all people and goods enter or exit the Territory through one of its seaports or airports. The Virgin Islands Port Authority (VIPA) is a semi-autonomous and financially independent organization that operates and maintains the airports, harbors, and a majority of the public seaports within the territory (U.S. Virgin Islands Port Authority 2018). VIPA operations are not funded by the tax base but instead must obtain revenue from services and user fees in order to be self-sufficient (and non-profit).

Passenger travel between the islands is primarily by aircraft and ferry. There are two main airports in the USVI: the Cyril E. King Airport on the southwestern side of STT (approximately 800,000 passengers annually) and the Henry E. Rohlsen Airport on the southwestern side of STX (approximately 250,000 passengers annually). There is no airport on STJ.

There are a number of marine port facilities on each island (for a comprehensive list, see the VIPA website, http://www.viport.com) serving both tourist and commmercical needs.

Cruise Ships. The USVI is a popular destination for cruise ships, and the associated tourism is an important component of economic activity in the Territory. Although there is no 'home porting' in USVI for cruise ships (this happens in nearby Puerto Rico and Florida), the USVI is often a first call en route.

St. Thomas is one of the most popular cruise ship destinations in the Caribbean. During peak season, STT receives 15-20 cruise ships per week (almost double the 7-10 ships per week in the off-peak season). In STT, there are two VIPA-operated ports that can receive cruise ships. The Austin "Babe" Monsanto Marine Terminal, located in Crown Bay to the west of Charlotte Amalie, has two docks and can accommodate three cruise ships simultaneously (including one berth capable of supporting an Oasis-class ship, currently the largest size in service). In Charlotte Amalie Harbor, a former U.S. Navy terminal now called The

Waterfront can accommodate yachts and other luxury vessels, mini-cruise ships and cruise ship tenders. Collectively, there are five berths in STT capable of handling cruise ships.

In Charlotte Amalie, the West Indian Company Limited (WICO; see www.wico-ltd.com) is a wholly owned subsidiary of the Virgin Islands Public Finance Authority (PFA) that operates a port facility with a cruise ship pier, shopping mall and commercial rental complex. WICO was acquired by the GVI in 1993, and is organized as a public corporation, governed by its own Board of Directors and Chief Executive Officer positions which carry fiduciary responsibility. The "WICO Berth is a 3,300 ft Marginal Protected Wharf with 30-34 ft depth alongside" (The West Indian Company Limited 2018) and can handle three large cruise ships.

In contrast, St. Croix used to be a popular destination for cruise ships, but the island currently receives relatively few port calls. In STX, the Ann E. Abramson Marine Facility in Frederiksted is the only port capable of receiving cruise ships. This port can simultaneously accommodate two cruise ships—either a single Voyager-class ship along with a smaller one, or two smaller cruise ships. The port is also equipped to receive a submarine.

Passenger Ferries. Water ferries provide local service between the islands of the USVI, as well as to the British Virgin Islands (BVI) and Puerto Rico. Each island in the Territory has one or more ports that currently support ferry service.

- Christiansted, STX: The Gallows Bay Dock serves passenger ferries as well as small cargo vessels traveling between STX and other Caribbean islands. This dock also accommodates mini-cruise vessels, small inter-island sloops, private yachts, and U.S. Coast Guard vessels.
- Charlotte Amalie, STT: The Edward Wilmoth Blyden IV Marine Terminal is located on the waterfront and serves as the primary hub for seaplane service as well as ferry service between the USVI and the BVI, and between STX, STT, and Puerto Rico.
- Red Hook, STT: The Urman Victor Fredericks Marine Terminal is located on the eastern end of STT and primarily serves passengers traveling by ferry between STT and STJ, and STT and the BVI.
- Cruz Bay, STJ: The Loredon Lawrence Boynes Sr. Dock supports ferry service to Red Hook and Charlotte Amalie.

Cargo Shipping. Most of the consumables, including food, are imported to the Territory, making cargo shipping a vital concern for Virgin Islanders. The USVI also serves as an important transshipment port for cargo moving to the East and South Caribbean. In addition, many cruise ships use the USVI as a provisioning port because the loading costs are significantly lower than in the U.S. mainland or elsewhere within the region.

Container cargo transport service is currently provided by two companies—Tropical Shipping (http://www.tropical.com/) and Crowley Maritime (http://www.crowley.com)—both operated out of Florida.

On STX, the primary port for cargo movement is the Wilfred "Bomba" Allick Port and Transshipment Center, located on the south shore of St. Croix next to Limetree Bay Terminals, LLC. This port is a hub for commercial and industrial marine activity on STX. It also serves as a transshipment center to many other locations.

On STT, the primary port for cargo movement is the Crown Bay Cargo Port—a 20-acre facility used for handling containerized and general cargo. This port serves as a transshipment port for cargo being shipped to many of the other Caribbean islands, and it also is a collection point for empty cargo containers before going back to the mainland. The Urman Victor Fredericks Marine Terminal in Red Hook, STT also has a dock equipped with a roll-on/roll-off ramp that is used to transport vehicles and other cargo between STT and STJ.

On STJ, the Theovald Eric Moorehead Dock and Terminal—in Enighed Pond, adjacent to Cruz Bay—has been the primary cargo terminal for the island since 2006. The Victor William Sewer Marine Facility (also called "The Creek") was the primary cargo terminal on St. John until 2006. It currently serves as a berthing port for passenger ferries and tenders, and is also used for inspections.

4.2 Road Systems

Surface transportation in the USVI is managed by the Department of Public Works (DPW) which is home to the construction, engineering, and operations branch of the local government. The DPW consists of four offices: Highway Engineering, Transportation, Engineering, and Construction. The most recent planning document is the 2040 Transportation

Plan (USVI Department of Public Works 2014), which provides a detailed overview of the territory and its demographics, land use, and other factors affecting transportation needs. As noted in the report (p. 45),"The existing transportation network includes roadways, bridges, transit, sidewalks, other bicycle and pedestrian facilities, harbors, and airports." Notably, whereas VIPA is responsible for the seaports and airports themselves, DPW is responsible for much of the supporting landside physical infrastructure.

The automobile is the preferred mode of transportation within each island in the USVI; from 2006 to 2016, registered vehicles increased 7.6% (Bureau of Economic Research 2017). There is limited public transit, primarily in the form of bus service. Privately operated open-air 'safari buses' follow informal routes and provide inexpensive ($1 fare) shared transportation. Although unregulated, they are the de facto backbone for commuter traffic. Taxis also exist in the territory and are regulated by the Taxi Commission via medallions similar to the mainland United States. Car-sharing services such as Uber and Lyft are not prevalent within the territory.

The road network maintained by the DPW consists of "483 miles of federal aid highways and 310 miles of other public roadways. In addition to roadways, DPW maintains 19 bridges and culverts throughout the island" (USVI Department of Public Works 2014). With a staff of twelve and an annual budget of $16M, the DPW Office of Highway Engineering is similar to a state's Department of Transportation and focuses on federal routes and capital improvements. The transportation section also has a staff of twelve and is primarily responsible for mass transit and the territorial transportation improvement plan (i.e., an annual, 5-year plan approved by the federal government each year).

Surface transportation in the territory follows from the population demographics, economy, and terrain of each island, which are dramatically different.

STT. St. Thomas (Figure 29) is the most populated, the most topographically extreme, and has the most registered vehicles of the three islands in the territory (Gajewski 2018). Although only 13 miles in length, STT experiences frequent traffic congestion. A significant portion of the resident population lives on the eastern side of the island, however the port of Charlotte Amalie on the south side brings nearly two million visitors annually via cruise ships (USVI Department of Public Works 2014). During the peak tourist season, STT receives an additional 20,000 to 30,000 daily visitors on the island when cruise ships are in port. This surge in island population benefits the economy, however, further complicates traffic conditions and limits public transportation availability.

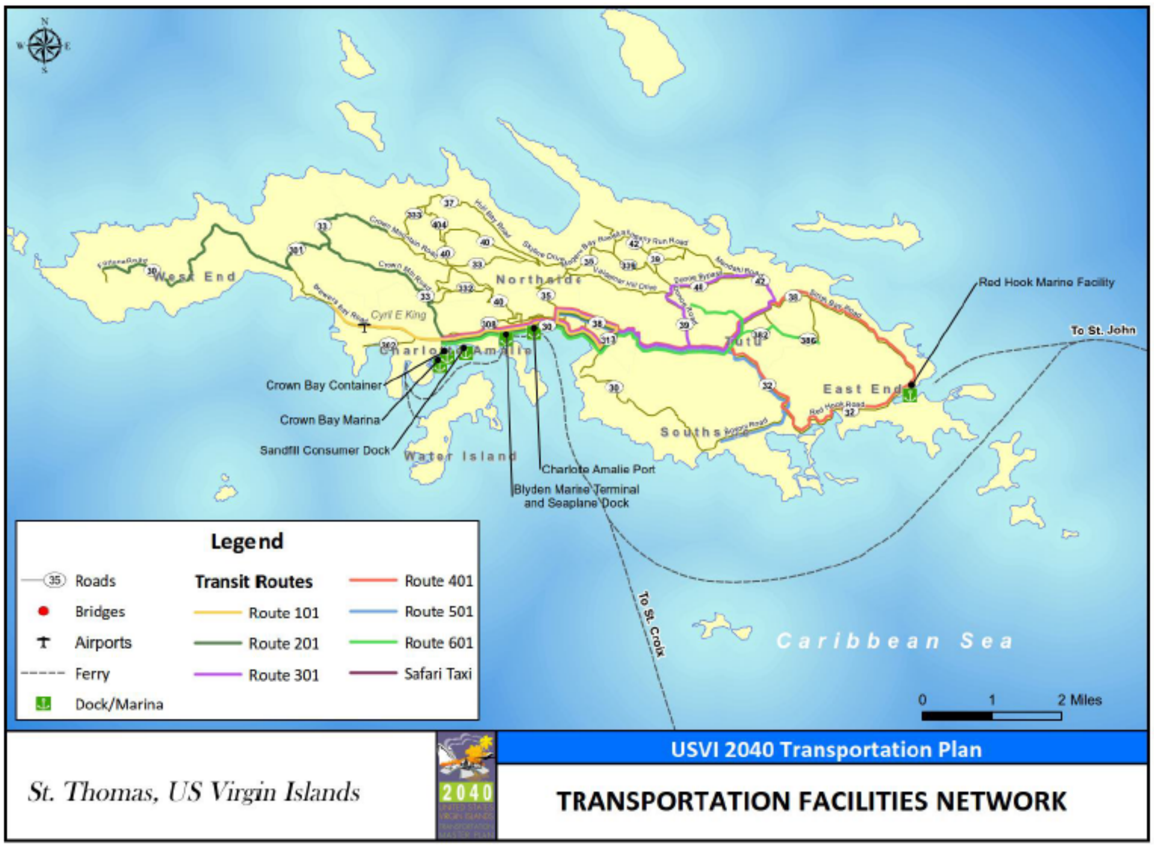


Figure 29. Road network on STT. Source: USVI Department of Public Works (2014).

STX. St. Croix (Figure 30) is vastly different from STT. Whereas STT is mainly a tourism hub, STX is more industrial and agricultural. The island is larger than STT, its topography is much flatter, and the island has fewer registered cars. Most of the islanders live in the population centers of Christiansted and Fredriksted, however, STX has more suburban sprawl than the other islands in the territory. The primary road arteries in STX are Melvin Evan and Queen Mary Highways; both of which run east-west. Many north-south roads connect to the primary arteries, which distribute traffic and reduce congestion.

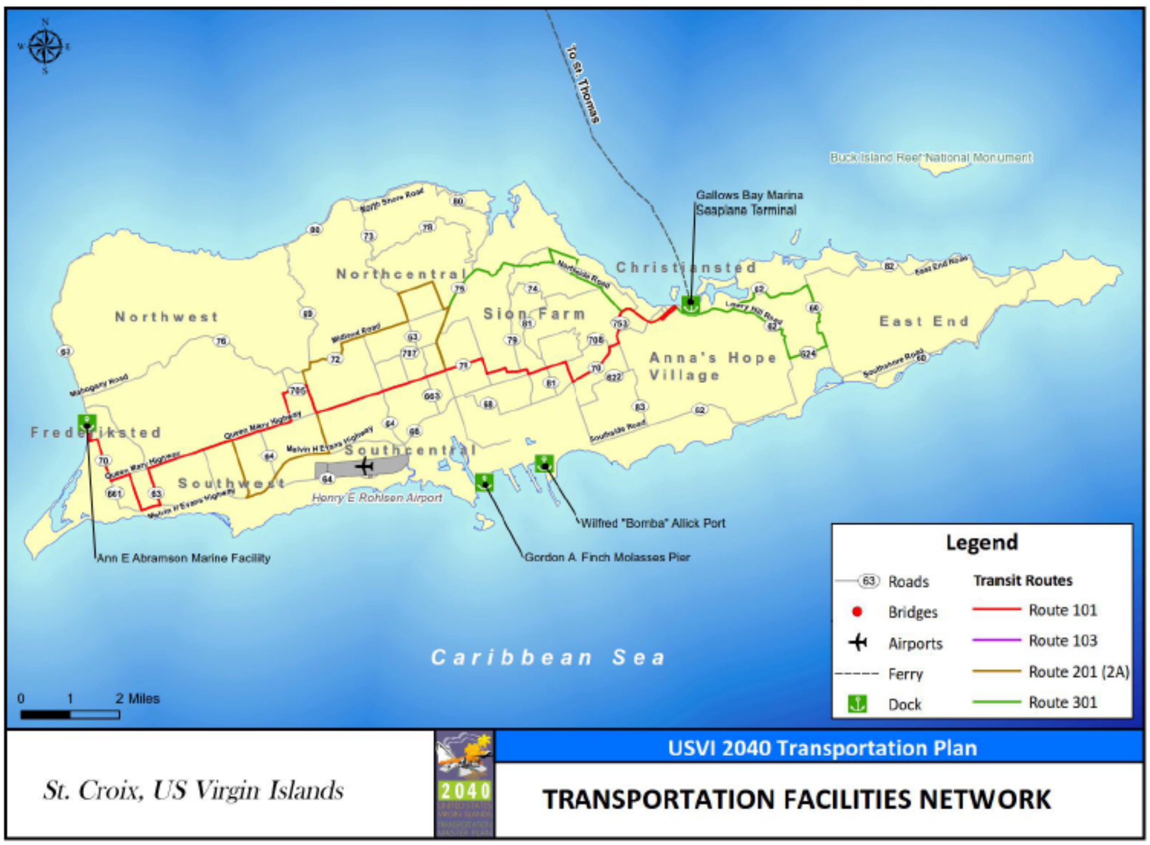


Figure 30. Road network on STX. Source: USVI Department of Public Works (2014).

STJ. The transportation system on St. John (Figure 31) is more restricted because more than 70% of this small island is a national park. There are two primary population centers—Cruz Bay on the western end and Coral Bay on the eastern end—with only two main routes connecting them. Thus, traffic congestion on St. John is a problem despite its relatively small population.

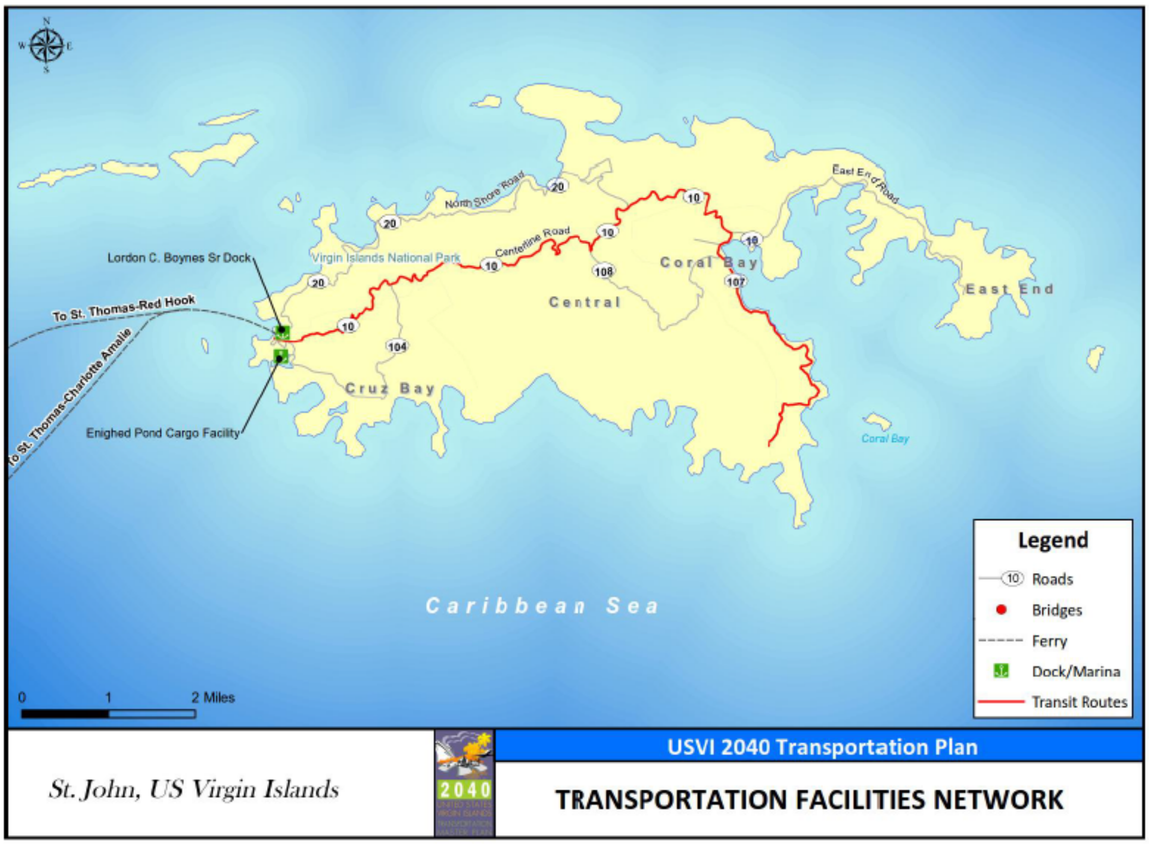


Figure 31. Road network on STJ. Source: USVI Department of Public Works (2014).

4.3 Territory Transportation Concerns

There are a variety of issues that constrain and/or challenge transportation infrastructure in the territory.

Finances. As with other parts of the USVI government, finances for transportation are very limited. The total Public Works budget for FY19 was $40M, of which $16M is federal funds. The Office for Highway Engineering spends the majority (approximately 95%) of annual budget on operating costs, leaving very little resources for maintenance (Gajewski 2018).

Geology. The island environment of the USVI presents various indigenous challenges to the transportation sector that makes management and maintenance of the transportation infrastructure particularly difficult and expensive. The geology of STT includes a very tough and ubiquitous rock—a volcanic breccia of bluish-gray color named scientifically *Louisenhoj rock* but known locally as 'Blue Bit' (Rankin 2002)—that can cost in excess of $300 per hour or $100-500 per yard to excavate. This additional cost for excavation, when added to the already high cost for materials, labor, and energy, makes many public works projects cost prohibitive.

Erosion. In addition to the geology of the islands, erosion plays a significant role in the degradation of the existing infrastructure. The main factors contributing to increased erosion in the territory is a lack of roadway shoulders, steep terrain, cut and fill earth work without establishing retaining walls, limited set-backs, and very little topsoil. All of these factors increase the likelihood for landslides after rainstorms; some roads on STT are still washed out from Hurricane Irma (see Figure 32). While newer technologies and techniques exist to combat this issue, barriers to implementation include shortages in highly skilled workers and local resistance to changing current practices.

Drainage. Another persistent problem for the DPW is poor drainage across the Territory. The USVI experiences a lot of rainfall, mostly at high intensities; mean annual rainfall for the territory between 1981-2010 ranges from 28.81-47.89 inches per year, depending on the island and elevation (National Oceanic and Atmospheric Administration 2018). As a result of the high intensity rainfall, heavy surface runoff tears up the existing asphalt and creates streams of debris that clog swales, guts, drainage culverts, and laterals. As detailed in Section 3.3, downstream effects of debris runoff associated with poor drainage results in clogged, collapsed, and broken wastewater treatment lines, as well as damaged pumping stations. Because the DPW has a shortage in personnel and resources for proactive maintenance, the current strategy is reactive in nature, where the department waits until there is a blockage and/or problem and then only restores it to its previous condition. These lack of resources result in an inability to clear swales, guts, and laterals at the prescribed interval

Figure 32. Left and Center: A washed out road and culvert on St. Thomas, as a result of Irma, still left in disrepair more than nine months after the hurricanes, June 2018. Right: A drainage culvert, part of the 'guts', on St. Thomas, remains full of debris.

of twice per year (Gajewski 2018) and clear excess silt buildup in the bays. Even if the DPW wanted to develop a proactive maintenance plan, there currently is no good inventory of all of the drainage infrastructure on the island; however, an ongoing research effort at UVI is developing this inventory for STT as an integrated part of a territory transportation inventory (Guannel 2018). In order to modify the current system, it is believed that the inventory of the drainage system is the first step to fixing the territory's drainage problems (Gajewski 2018). There is also a need for new construction that must consider new techniques and technologies, storm water retention, and more efficient and effective drainage solutions based on drainage and usage data.

Limited Local Resources. The DPW has very limited personnel and equipment, and it therefore must contract most of its work, which is generally more expensive. In addition, the DPW has no mechanism to quickly get contractors working and paid in the event of an emergency or serious event. This coupled with the high cost to bring material, equipment, and labor creates strong disincentives for contractors to come to the territory.

There are additional constraints on the availability of materials and equipment. The Territory only has one asphalt plant (with costs ranging from $200-300 per yard) and one concrete plant (with costs at greater than $200 per yard), both of which are expensive compared to the mainland. Quality control at each of these plants is reportedly problematic, and there does not appear to be policy or procedures to ensure contractors and local plants are using and producing federally compliant materials.

4.4 Hurricane Aftermath: Challenges and Opportunities

Like other systems across the territory, the hurricanes of 2017 complicated an already stressed transportation infrastructure. As noted by the USVI Hurricane Recovery and Resilience Task Force (2018, p. 17): "Airports on St. Croix and St. Thomas closed for two weeks and reopened with only limited capacity. Seaports closed for three weeks due to the sinking of more than 400 vessels; roads blocked with debris and the loss of power to traffic lights—or the lights themselves—resulted in a more than a sevenfold increase in crashes at intersections."

Ports. Recovery time in the seaports following a disaster is critical for two reasons. First, there is typically a need to bring in materials to support response and recovery. Second, the absence of cruise ships (particularly in STT) is costly to the local economy.

The United States Coast Guard (USCG) Captain of the Port (headquartered in San Juan, Puerto Rico) closes and opens the ports in the territory, working alongside the local Area Maritime Security Council. Before the Port in Charlotte Amalie could reopen, the channel had to be cleared of debris and surveyed so it was safe for cruise ships and other large vessels. Even once the port was opened for traffic, the container port remained offline for a significant period of time because the electric grid was down. In contrast, the electric distribution feed to the cargo terminal in STX is underground, which reduced the recovery time there.

Although the 'in water' infrastructure generally held up well in STT, there was considerable damage to the shopping centers, restaurants, and inland buildings. Because the cruise industry relies heavily on high-quality, on-shore tour experiences, the slow recovery of the downtown area in Charlotte Amalie meant that cruise ships stayed away longer than was physically needed. As of June 2018, cruise vessel traffic was still lower than in the past (see Figure 33, Right). At the same time, the cruise industry as a whole is currently experiencing considerable growth, limited only by number of available ships (Cartwright

2018). It remains to be seen the extent to which the USVI can tap into this potential growth in tourism.

Passenger travel by air remains considerably lower than in the past (see Figure 33, Left) because of a reduction in available flights to the Territory and the still-limited availability of hotels, restaurants, and other facilities, some of which are not scheduled to reopen officially until 2020.

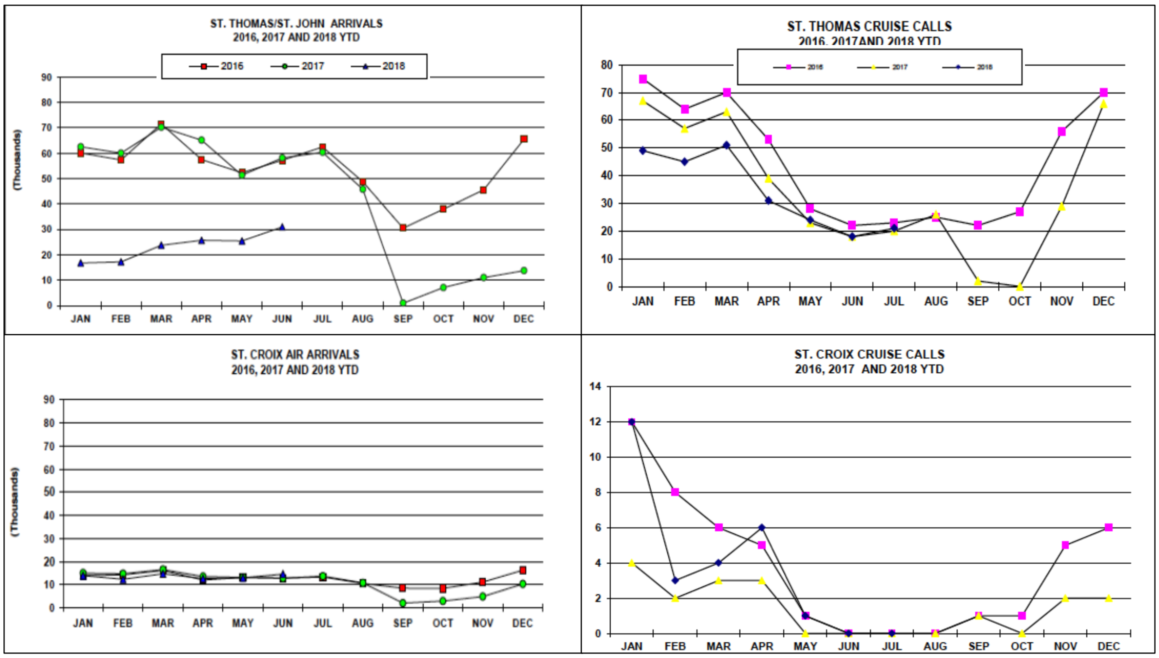


Figure 33. Left: Monthly passenger arrivals by air, January 2016 - June 2018 (Source: reproduced from U.S.V.I. Bureau of Economic Research 2018a). Right: Monthly cruise ship arrivals, January 2016 - June 2018 (Source: reproduced from U.S.V.I. Bureau of Economic Research 2018b).

Roads. The storms caused significant problems for the road system. Whereas Hurricane Irma's winds brought down trees, power lines, and clogged up the drainage, Hurricane Maria's heavy rains caused significant damage to the roadways themselves. The inability of response and recovery crews to move through the Territory to access key facilities and infrastructure were reported to be a significant problem across the other infrastructure sectors.

For months following the hurricanes, many of the roads across the territory were cleared but could only support a single lane of traffic. In some cases, remnants of debris remained alongside the roadways for more than six months before being completely cleaned up. As noted, the DPW has very little heavy equipment for clearing debris from the roads (e.g., bulldozers, front-end loaders, dump trucks, etc.) and relies on contractor support for nearly all of this type of work. In fact, all of the DPW equipment broke within two days of road clearing operations following the storms (Gajewski 2018). As of June 2018, half of the signalized intersections were still not back online, leading to a 700% increase in automobile accidents from the previous year (Gajewski 2018). From a DPW perspective, the hurricane recovery effort has been slow; long lead-times for contracting and procurement is believed to slow the recovery by an additional 6-to-12 months, well beyond the 2018 hurricane season.

5 USVI Telecommunications

Unlike energy and water infrastructures that are centrally owned and operated by WAPA, telecommunications (telecom) infrastructure is spread among a variety of stakeholders. The telecom sector in general is characterized by strong competition, and as a result owner-operators have considerable economic incentive to hide or obscure information about their systems. This section provides an overview of these players and infrastructure, as understood by domain experts (Price 2018); see USVI Hurricane Recovery and Resilience Task Force (2018) for additional details.

Telecommunications in the USVI is provided by a number of undersea cable systems that make landing at different locations in the Territory (see Table 1). For example, six undersea fiber cables, originating from New York, Florida, Panama, Brazil, and Puerto Rico land north of Fredriksted at Butler Bay, STX (Figure 34). CenturyLink and AT&T are the private sector owners of these landing sites and supply approximately 8-10 Terabits of telecom capability to the Islands through the main public sector provider, Virgin Islands Next Generation Network (viNGN). AT&T has another landing site in Magen's Bay, Peterborg, STT.

Figure 34. One of the two fiber cable landing sites - North of Fredriksted. Photo: NPS, March 2018.

Undersea telecommunications cabling connects directly to STT and STX, and STJ is con-

Table 1. Undersea Cable Systems Connected to the U.S. Virgin Islands.

Official name Ready for service date Cable system length	**Owner(s)**	**Landing points**
Americas-I North 1994 2,012 km	Embratel, AT&T, Verizon, Sprint, CANTV, Tata Communications, CNT, Orange, Portugal Telecom, C&W Networks, Telecom Italia Sparkle, CenturyLink	**Magen's Bay, St. Thomas, USVI**; Vero Beach, FL
Americas-II 2000 8,373 km	Embratel, AT&T, Verizon, Sprint, CANTV, Tata Communications, CNT, Orange, Portugal Telecom, C&W Networks, Telecom Italia Sparkle, CenturyLink	Camuri, Venezuela; Cayenne, French Guiana; Fortaleza, Brazil; Hollywood, FL; Le Lamentin, Martinique; Miramar, Puerto Rico; Port of Spain, Trinidad and Tobago; **St. Croix, USVI**; Willemstad, Curaçao
Columbus-II b 1994 2,068 km	n.a.	**Magen's Bay, St. Thomas, USVI**; West Palm Beach, FL
Global Caribbean Network 2006 n.a.	Leucadia National Corporation, Loret Group	Baillif, Guadeloupe; Jarry, Guadeloupe; Saint Barthelemy, Guadeloupe; Saint Martin, Guadeloupe; San Juan, Puerto Rico; **St. Croix, USVI**
Mid-Atlantic Crossing 2000 7,500 km	CenturyLink	Brookhaven, New York; Hollywood, Florida; **St. Croix, USVI**
Pan American 1995 7,225 km	AT&T, Telefonica del Peru, Softbank Telecom, Telecom Italia Sparkle, Sprint, CANTV, Tata Communications, Telefónica de Argentina, Telstra, Verizon, Entel Chile, Telecom Argentina, Telconet, Instituto Costarricense de Electricidad, C&W Networks, Embratel, CNT	Arica, Chile; Baby Beach, Aruba; Barranquilla, Colombia; Colón, Panama; Lurin, Peru; Panama City, Panama; Punta Carnero, Ecuador; Punto Fijo, Venezuela; **St. Croix, USVI**; **St. Thomas, USVI**
South American Crossing / Latin American Nautilus 2000 20,000 km	Telecom Italia Sparkle, CenturyLink	Buenaventura, Colombia; Colón, Panama; Fort Amador, Panama; Fortaleza, Brazil; Las Toninas, Argentina; Lurin, Peru; Puerto Viejo, Venezuela; Rio de Janeiro, Brazil; Santos, Brazil; **St. Croix, USVI**; Valparaíso, Chile
Southern Caribbean Fiber 2006 n.a.	Digicel	Baie-Mahault, Guadeloupe; Baillif, Guadeloupe; Basseterre, Saint Kitts and Nevis; Canefield, Dominica; Chaguaramas, Trinidad and Tobago; Gustavia, Saint Barthélemy; Kingstown, Saint Vincent and the Grenadines; Le Lamentin, Martinique; Needham's Point, Barbados; Port Salines, Grenada; Rodney Bay, Saint Lucia; San Juan, Puerto Rico; **St. Croix, USVI;** St. John's, Antigua and Barbuda; St. Louis, Saint Martin
St. Thomas-St. Croix System 2013 183 km	Virgin Islands Next Generation Networks, Inc.	**Banana Bay, USVI; Brewer's Bay, USVI; Christiansted, USVI; Flamingo Bay, USVI; Frederiksted, USVI; Great Bay, USVI; Vila Olga, USVI**
Taino-Carib 1992 186 km		Condado Beach, Puerto Rico; Isla Verde, Puerto Rico; **Magen's Bay, St. Thomas, USVI**

(source: TeleGeography, www.submarinecablemap.com)

nected indirectly through STT. Overall, the telecommunications infrastructure in the USVI territory is a complicated system with service, functionality, and oversight separated between public and private sectors.

5.1 Public Sector

The public telecommunications sector is comprised of three entities for which the government has responsibility and oversight: viNGN, USVI Bureau of Information Technology (BIT), and the Public Broadcast Network.

viNGN. Funded by federal government bonds, viNGN provides middle-mile fiber for broadband distribution capability to the private sector across the islands. viNGN has 220 miles of buried fiber across all three islands, constituting approximately 60% of its fiber capacity (USVI Hurricane Recovery and Resilience Task Force 2018). During the hurricanes, fiber access points and undersea cabling suffered minor damage, and the buried telecommunications cabling fared well. However, aerial lines on WAPA power poles were 90% damaged or destroyed (USVI Hurricane Recovery and Resilience Task Force 2018). As a result of the damage, viNGN worked with FEMA and WAPA to include provisions for future underground power line projects to include burying fiber and installing conduit for future expansion in FEMA's 404/406 coordination plan (Federal Emergency Management Agency 2018a).

BIT. As the information technology arm of the USVI government, BIT was meant to be the one-stop-shop for government IT needs; however, it primarily serves as the government's main telecommunications service provider between the islands, via microwave and some viNGN capability. BIT was formed via a law, but nothing in that law specifies that government agencies have to use them, and there are no restrictions that prevent government agencies from acquiring their own IT capabilities, technicians, applications, or contractors. As a result, BIT has been unable to establish a common acquisitions or cybersecurity plan, create real IT situational awareness across the government, or create IT commonality and interoperability between agencies. Current efforts to fix this problem include a study to assess the overall IT infrastructure within the territory and generation of a USVI enterprise-level IT plan.

In addition to the IT infrastructure, BIT is also responsible for the public safety land-mobile radio (LMR) network, consisting of five towers on STX, five on STT, and one on STJ. The USVI owns only two of the 11 towers; SBA Communications Corporation (SBA) owns the others. The network was built in 2010, but a 2013 study (Heath 2013a,b) found the network suffered from numerous dead spots, due to a tower being too short, as well as the network being in disrepair, with many tower alignment issues and aged and/or obsolete equipment. The hurricane season added problems on top of this state of disrepair. On STJ, the 180-foot SBA tower, designed to withstand 200mph winds, was completely destroyed. On STT, the two damaged towers were recovered and returned to service, but repairs from incurred damage have been slow. This damage, coupled with coverage and congestion issues led to Tate Communications recommending three options for rebuilding the network (Tate Communications 2017):

1. Find other equipment to band-aid the network back together (least expensive option);
2. Partial reconstruction and band-aid fixes across the entire network; and
3. Completely rebuild with a new, digital P25 network (estimated at ~$3 billion).

There have been other proposals (Price 2018) to FEMA for system upgrades that included erecting a new tower to overcome dead spots in Cotton Valley on STX (gain of 50-75 ft.) and redoing the radio network to include digital system capabilities for police, fire, emergency management service (EMS), and FEMA.

Public Broadcast Network. WTJX Channel 12 (television) and WTJX-FM (National Public Radio) comprise the Virgin Islands Public Broadcasting System and operate as a semi-autonomous government agency. The station is an affiliate of the private, non-profit Public Broadcasting Service (PBS) and also receives funds from the Corporation for Public Broadcasting (CPB). Most content is received from satellite download or undersea telecommunications cables and is then blanket transmitted from STT to the entire territory. The main production studio is located in STT and was totally destroyed by hurricane Irma, along with one of two 100-foot transmission towers. To date, the Public Broadcast Network is working with the Federal Communications Commission (FCC) to fund reconstruction of the destroyed tower and with FEMA for reconstruction of the production studio. The main offices and an additional production studio are located in the Estate Richmond area of STX.

5.2 Private Sector

The private sector is entirely different from the public sector and more complex (Price 2018). The local government and U.S. government agencies have had difficulty getting data and information from private sector providers post-hurricane, especially from cellular providers. In response to this, the Public Service Commission established the Hurricane Infrastructure

Team (HIT) in an effort to encourage public and private cooperation in recovery efforts. To incentivize participation, the Commission coerced private carriers by threatening fines for outages lasting longer than 72 hours if the same carriers did not participate in the HIT. Despite this, very little information was actually shared.

Overall, there are three main telecommunication providers in the territory—AT&T, Sprint, and Viya—as well as 14 small internet service providers.

AT&T and Sprint. Prior to and post-hurricane, AT&T and Sprint have physical assets located in the territory providing 4G coverage. AT&T coverage is reportedly better than that of Sprint, who is focused on establishing services for the tourist population areas, resulting in spotty coverage overall across the territory. Between the two providers, AT&T has a larger footprint with an established landing site (two submarine telecom cables) at Butler Bay (south of CenturyLink) and an undersea cable connecting STX and STT. It is believed (Price 2018) that the USVI government utilizes AT&T's cables for their primary communication, but this is not verified. T-Mobile and Verizon do not have any physical assets in the territory and therefore, must partner with AT&T and Sprint via roaming agreements to service their customers in the territory. Both AT&T and Sprint suffered damage in the hurricanes, including damaged and/or destroyed towers and antennas.

Viya. As a fairly new company, Viya provides wireline (telephone), mobile, internet, and cable television services across the territory. Viya is the USVI communications subsidiary of ATN International, Inc. and the incumbent local exchange carrier (ILEC); Viya has no competitive local exchange carrier. As the ILEC, Viya is the designated wireline provider of dial tone in the territory. With this designation, Viya receives funds from the FCC and other carriers (AT&T and Sprint) to maintain lifeline services and provide wireline service capability to everyone in the territory. For wireline services, Viya receives off-island communications through CenturyLink and then provides dial tone through the local exchanges through either copper wire (older infrastructure) or hybrid fiber coaxial (HFC). Prior to the hurricanes, Viya was working towards replacing all copper wire with HFC, however, because wireline HFC was on aerial electrical poles, most was damaged or destroyed. As part of the recovery, Viya is not installing any new copper wire and plans to move all customers to HFC though it is unclear if Viya will work with WAPA, similar to viNGN, to bury HFC lines alongside underground electrical projects. Of note, Viya has no established relationship with viNGN because they are a middle-mile fiber competitor. Estimated penetration for wireline services in the territory is 30-40% and services were restored to STT in November 2017, STX in December 2017, and STJ in January 2018. Cable television services that were largely wiped out in the storms are moving to HFC or to a fiber network, however, the project is going very slowly.

Internet Service Providers (ISPs). In addition to Viya, two main ISPs exist in the islands; Broadband VI (BBVI) and SmartNet. BBVI is based in and mostly services STX, however, they do have some customers on both STT and STJ. SmartNet is located and primarily services customers on STT, though the company has some customers on STX. Apart from the two main ISPs, there are 12 other small providers.

New public safety network. In 2017, AT&T was awarded a contract to create a separate public safety network (FirstNet, network for first responders) that uses a new communications spectrum band (digital radios) for public service providers to communicate with one another in the event of another disaster (Pereira 2017).

5.3 Resiliency of Communications System

Communications are critical to response and recovery efforts. Nearly everyone interviewed for this technical report commented that (1) communication systems performed poorly both during and immediately after the hurricanes, and (2) improved resilience for communications is a top priority for investment. More than a year after the storms, there remains concern that communications infrastructure is still vulnerable. Telecommunications towers, antennas, and HFC on aerial poles are still vulnerable to high winds; existing copper wire is susceptible to flooding; and backup electrical generator plans are still dependent on uncertain fuel distribution.

One challenge for the telecommunications sector is that FEMA is restricted in the way it can use its assets to support private sector companies. It is believed (Price 2018) that system resilience would be greatly improved if FEMA had increased flexibility to support private infrastructure companies, such as AT&T, Viya, and CenturyLink, to ensure their continuity of service. For example, could FEMA funding be used to create a cache of generators owned, maintained, and prioritized for distribution by the USVI government to critical infrastructure assets, such as telecommunications, in times of need?

6 Achieving Critical Infrastructure Resilience

Our basic approach to improving critical infrastructure resilience involves two steps: (1) establishing an operational view of the system, and (2) using it to identify and overcome barriers to resilience. Our starting point is to understand 'how things work' as viewed by the owners and operators of each infrastructure system. We start here because experts and non-experts alike can only begin to make successful plans for infrastructure resilience when they understand the operational capability of the system to deliver service, even in the presence of disruptive events (for background, see Alderson et al. 2014, 2015) Sections 2-5 provide this investigation for USVI energy, water, transportation, and communication systems.

The reason for developing an operational view is to support decisions for making critical infrastructure more resilient. A near term goal is to support ongoing recovery and adaptation activities on the islands. Our second step focuses on setting priorities and identifying resilient infrastructure solutions by considering the barriers to operational resilience that may impede progress. A focus on overcoming barriers is more about ensuring stakeholder needs for resilience are implemented effectively, rather than promoting a particular type of solution. Our second step towards improving operational resilience, then, involves identifying where barriers to resilience (introduced in Section 1.2.3) may exist and offer ways to circumvent them.

6.1 Barriers to Operational Resilience in the USVI

Here we provide a non-exhaustive list of some of the barriers to operational resilience revealed by the operational view of energy, water, transportation, and communication systems.

6.1.1 Energy Systems

Assessing (a Lack of) Resilience. The tensions discussed in Section 2 for USVI energy systems remain roadblocks to long term infrastructure resilience. Prior to the writing of this report, STT/STJ and STX energy systems were regarded by experts as the most well-studied critical infrastructure systems on the islands. Associated infrastructure vulnerabilities involving access to primary fuels and generation faults were well documented since the early 2010s. Still, energy infrastructure vulnerabilities that are recognized but not acted upon can undermine attempts to 'build back better' and survive future disasters. Continued reliance on a single power generation plant with oversized turbine generators will be a barrier to operational resilience by exacerbating difficulties in fuel procurement, efficient turbine operation, generation-demand matching, and synchronous generator control. Post-hurricane recovery and adaptation efforts to install additional distributed generation may alleviate this vulnerability.

Hurricanes Irma and Maria also revealed vulnerabilities in STT/STJ and STX transmission and distribution infrastructure that impede operational resilience. Transmission infrastructure on STT/STJ and STX has a looped structure to survive any single line failure, but many primary feeders in both power systems do not. These power lines that connect transmission to customers have a radial structure vulnerable to blackout from a single fault along the line. This problematic design combined with the above ground installation of most USVI feeders left T&D systems particularly vulnerable to hurricane winds. Implementing new physical structures used to support power infrastructure and system designs to re-dispatch electricity would support both power grids. Post-hurricane recovery and adaptation efforts to underground feeder power lines and add additional system connectivity may alleviate this vulnerability.

Additional unknown barriers to resilience may lie at the intersection between electric power systems and the critical loads they serve. Critical loads like water pumps, hospitals, schools, ports, and traffic signals among others tend to be a small fraction of total electric power demand. However, many critical loads have unique demand profiles and needs that make them difficult to serve compared to normal commercial/industrial and residential customers. Some loads critical to the island like water systems and ports are also critical to STT/STJ and STX power systems operations, making them even more important for reliable electricity supply. Local stakeholders–particularly the USVI Energy Office and the VI Water and Power Authority (WAPA)–indicated that water and its interconnection with energy was a topic of considerable concern. For example, the water source needed for cooling generators in both STT/STJ and STX power systems is provided by nearby reverse osmosis plants that depend on grid electricity to operate. These kinds of service-based and geographic interdependencies exist across each island, but no work has ever documented their implications for infrastructure resilience. Due to a lack of attention, this vulnerability may remain an issue in the future.

Economic (Dis-)Incentives. The short- and long-run economics of WAPA's energy operations appear to be unsustainable, creating a significant barrier to resilience. There will be no way to ensure long term resilience if WAPA continues to lose money.

An important economic barrier is the inconsistent cash flow payments for electricity services. WAPA's ability to maintain a robust operations and maintenance (O&M) program is directly tied to its ability to sustain necessary cash flows. Unfortunately, WAPA has few 'staple loads' with constant high demand, and the GVI—WAPA's single largest customer—does not always pay its bills. This means WAPA must maintain the customers it already has, find new customers to cover increasing costs, and find ways to recover unpaid bills. A barrier to resilience is simply fixing chronic cash flow problems resulting from operation of the STT/STJ and STX power grids to ensure these systems remain funded to provide electricity during disasters.

Finding the right balance of revenue captured by the Levelized Energy Adjustment Clause (LEAC) and renewable energy generation also affects WAPA's economic position. Many recommendations for energy resilience involve greater deployment of distributed solar photovoltaic and wind technologies. This is a technological challenge that may exacerbate the economic burdens of WAPA. Most large customers operate off-grid during normal operations and only use the STT/STJ and STX power systems as backup, and there is no effective mechanism for charging these customers for the solar power they produce (e.g., feed-in-tariffs). This means WAPA does not recoup enough revenue from these customers to fund O&M programs because the majority of WAPA revenue comes from the LEAC surcharge on electricity consumption. Increasing use and cost-effectiveness of renewable energy generation in the USVI will incentivize more large customers and government facilities to go off grid. A barrier to operational resilience is balancing the economics of using the LEAC to recoup fuel costs and the increasing deployment of renewable energy generation.

6.1.2 Water Systems

Water infrastructure systems—including stormwater, potable water, and wastewater—have received less attention than the other infrastructure sectors over the last decade, but the damage inflicted by the 2017 hurricanes exposed their vulnerabilities. The Governor's Task Force has recommended 11 water initiatives for WAPA and another 15 wastewater initiatives for VIWMA. These are mostly aimed at restoring and improving the existing systems. However, there is a recognition that these systems are in need of a major redesign and expansion, one that aligns their capability with the current needs of the population. In the short term, a primary challenge is going to be prioritization of the many initiatives that compete for the same resources. In the longer term, these systems face significant economic challenges that come from a lack of appropriate funding and/or increased competition.

6.1.3 Transportation and Communications

The transportation and communications sectors each represent a diverse set of services that are owned and operated by a mix of public and private service providers. This makes them qualitatively different from the energy and water sectors. In general, it is difficult to get operational details from the private service providers, and there remains significant distrust of the private sector to sharing information about systems that are believed to be a source of competitive advantage.

Transportation infrastructure (i.e., roads, seaports, airports) is highly visible to the public, even if decision-making by private carriers (airlines, shippers) is more opaque. As a result, the barriers to operational resilience seem not to be a lack of knowledge about system vulnerability or what do to about it. Rather, it appears to be a lack of available resources for transportation systems—including people, materials, equipment, and funds—that makes progress slower than it could be otherwise. Further investigation is required to understand more fully whether this is a consequence of insufficient economic incentives and/or governance issues.

In contrast, investment in telecommunications infrastructure is strongly motivated by the competitive nature of the sector as a whole. However, a lack of public knowledge about the system contributes to a lack of awareness about resilience, and it also makes an operational analysis of the system more challenging.

6.2 What we can do about it

Addressing the four barriers to resilience requires extensive efforts across diverse stakeholders. The Governor's Recovery and Resilience Task Force demonstrates this significant need by advancing 228 initiatives to recover and adapt USVI critical infrastructure systems (USVI

Hurricane Recovery and Resilience Task Force 2018). Addressing how each initiative may help overcome each barrier is beyond the scope of this work. Instead, on a smaller scale, here we focus attention on several smaller efforts that are being conducted collaboratively and synergistically and involve a variety of organizations including NPS, DOE, NREL, and Sandia.

6.2.1 Interdependent Water-Energy Infrastructure Analysis.

Overcoming barriers in water and energy infrastructure systems can be achieved with modeling and analysis to identify interdependencies that impact system operation. Issues with centralized generation and vulnerability of T&D systems are currently being dealt with by WAPA. The concern stakeholders share for water-energy systems is receiving less attention and is an important starting point for assessing whether there are latent infrastructure vulnerabilities that are not being considered in current resilience efforts. Interdependent infrastructure models that embed technical information about the demands and locations for customer service, the capacity and locations for supply, and the capacities and constraints on the ability to move these flows from supply to demand can help reveal vulnerabilities about the interdependent systems. Specifically, identifying new vulnerabilities can be supported by optimization models to prescribe normal operations for interdependent systems and predict future emergency scenarios. A prescriptive optimization model reconciles what the operator wants to do (the objective, e.g, minimize operating costs) with what the operator can do (the constraints, e.g., limited generator or transport capacity) to identify unanticipated vulnerabilities across interdependent systems. A predictive optimization model then uses this information to study how interdependent infrastructure systems may work in the future. This prescriptive operator model can discover alternate solutions for infrastructure operations when the usual pathways are damaged or unavailable.

With infrastructure models in place, assessing how vulnerable interdependent systems are amounts to a systematic analysis of ‘what-if’ scenarios involving the loss of one or more infrastructure components and measuring how built systems and operators may respond to these disruptions. Doing this exhaustively for a large system can be computationally expensive, but NPS has advanced specific mathematical techniques that solve for ‘worst-case’ disruptions without having to try them all (see Alderson et al. 2014). This is broken down into two parts.

(1) Consequence estimation. Typically, the first question of interest when addressing Barrier 1 is: *What will be the consequence if [Event X] occurs?* Here, consequence is most naturally addressed in terms of continued infrastructure function (e.g., who is without electricity and for how long?) but it can also be framed in terms of the economic or welfare impacts directly on the population. This type of investigation requires a set of potential events as inputs; these typically come from some type of preliminary notion about disaster scenarios or threats of concern. Extreme weather events (such as the storms of 2017) are obvious choices, but in general critical infrastructure systems can be catastrophically disrupted by events much smaller than a Category-5 hurricane.

(2) Vulnerability and resilience assessment. Perhaps more importantly, the modeling and analysis tools in this part of the project can be used for the discovery of events or scenarios that hurt the welfare of the USVI in particular ways. NPS has more than 30 years of experience developing so-called "attacker-defender" models for discovering disruptions that lead to worst-case consequences, even when system operators respond in the best manner possible (see Appendix A.3). These techniques can be used to assess all hazards—including natural disasters, accidents, technological failures, or deliberate attacks—and are designed specifically to identify critical interactions and dependencies between components before such disruptions catch stakeholders by surprise.

Current Progress. Interdependent infrastructure modeling efforts are underway to apply attacker-defender models to USVI electric power and water distribution systems. Since interdependent infrastructure models did not exist previously, NPS focused on initial model development in 2018. The newly developed models are documented in the masters thesis by Bunn (2018) to demonstrate cascading failures across water-energy systems.

The primary goal of this effort is to study USVI infrastructure operations and support a new understanding of systemic vulnerabilities in STT/STJ and STX electric power and water systems. There remains considerable work to gather the appropriate data, integrate it into a working model, perform the analysis, and communicate results to stakeholders. A long term goal is to extend the energy-water models to incorporate food supply chains (with emphasis on transportation and agriculture systems) to ultimately assess the resilience of combined energy-water-food systems for the territory. Additional systems, such as communications, may be included as stakeholders desire and needs arise.

6.2.2 Prioritization for Resilience Activities

Overcoming barriers in prioritization requires decision-making support for critical infrastructure recovery and adaptation activities. Identifying how to improve the resilience of the system first involves a systematic 'what-if' analysis of how potential investments–such as component 'hardening', redundancy, capacity expansion, or even new construction–mitigate the worst-case disruptions to the system. The types of 'what-if' analyses designed for consequence and vulnerability assessment can be used for prioritizing recovery and adaptation efforts: *What if we harden, expand, or add to the system in a particular manner?* That is, the same quantitative techniques for assessing resilience extend to the development of mitigation or investment plans. Given the rapid development of new technologies and concepts for infrastructure operation, it is imperative that decision makers have a means for quantitatively assessing the associated costs and benefits, in terms of reliability, robustness, and resilience.

Concurrent efforts supporting mitigation and investment decisions with a limited budget are being completed by experts from DOE, Sandia, NREL, UVI, and NPS. Specifically, Sandia and NREL experts are supporting renewable energy and microgrid deployment decisions in the STT/STJ and STX power grids with new analysis and design tools. Experts from the UVI are working with NPS to update USVI hazard preparedness and mitigation plans for all critical infrastructure systems on the islands. Associated with this work is new assessment of infrastructure vulnerabilities that will help prioritize adaptation initiatives for the next five years.

6.2.3 Incentives and Training for Resilience

Overcoming economic and governance barriers to resilience requires the incentive structures, rules, and organizations involved in infrastructure provision to adapt alongside built systems. New investments and economic incentives that improve system operation during routine circumstances and unexpected disruptions are necessary for long term critical infrastructure resilience. A number of different projects by DOE and related stakeholders are developing economic instruments that support WAPA operations and create long term funding structures for infrastructure resilience. Some examples include demand reduction incentives through energy efficiency initiatives aligned with the USVI Energy Office and EDIN Initiative that ensure investments in generation redundancy increase reliability.

There are other efforts to explore public-private partnerships with large companies, such as LimeTree Bay Terminals, to provide emergency generation capacity.

Overcoming governance barriers also requires evolution in the structure of organizations and the embedded knowledge among local experts. While infrastructure systems can change rapidly, there is no guarantee that the people who own, operate, and regulate them will adapt to the new order. This mismatch in operations is one of the most difficult things to manage in the near term. One way to circumvent this barrier is to train current experts and develop a new workforce that has an operational view of infrastructure systems and supports resilience in the long term. Both national labs and universities are well-positioned to provide new training programs that build local expertise in resilience. Specifically, Sandia National Laboratory experts are working to provide training workshops on the design and operation of microgrids to support local stakeholders to better utilize the technology. UVI and NPS are also working to enhance existing education programs to educate stakeholders about operational resilience and strengthen ties between university students and local infrastructure providers like WAPA. The combination of new workshops and educational programs will build-up local knowledge of resilience across all infrastructure sectors and also create a community of experts who have strong social ties. The community-building element of workforce development activities is crucial to long-term resilience, as collaboration and cooperation among infrastructure providers is a key need for surviving future disasters.

6.3 Conclusion

Although this report focuses on tensions and barriers that may jeopardize USVI critical infrastructure resilience, it is important to remember that *the people and systems in the USVI are already resilient*. The devastation brought by hurricanes Irma and Maria could have permanently crippled the community. Yet, the people of STT, STJ, and STX already recovered and continue to fight for a future that can survive even greater catastrophes. Resilience must have already existed somewhere in the islands to make it this far already. As the transition to a new USVI with new infrastructure systems continues, it will be important to maintain an outlook that things can and will be even better than they are. The intention of this report is to help ensure this better future.

APPENDIX: Additional Background

A.1 USVI Demographics

Infrastructure systems are designed to support the needs of a geographically distributed population. As a start to understanding the infrastructure demands in the USVI, it is important to consider some basic information about the size and geographic distribution of its population. The following data comes from the 2010 U.S. Census.

Table A.1. 2010 Population of the U.S. Virgin Islands.

US Virgin Islands	106,405
St. Croix Island	50,601
Anna's Hope Village subdistrict	4,041
Christiansted subdistrict	2,626
East End subdistrict	2,453
Frederiksted subdistrict	3,091
Northcentral subdistrict	4,977
Northwest subdistrict	4,863
Sion Farm subdistrict	13,003
Southcentral subdistrict	8,049
Southwest subdistrict	7,498
St. John Island	4,170
Central subdistrict	779
Coral Bay subdistrict	634
Cruz Bay subdistrict	2,706
East End subdistrict	51
St. Thomas Island	51,634
Charlotte Amalie subdistrict	18,481
East End subdistrict	8,403
Northside subdistrict	10,049
Southside subdistrict	5,411
Tutu subdistrict	6,867
Water Island subdistrict	182
West End subdistrict	2,241

(source: U.S. Census Bureau)

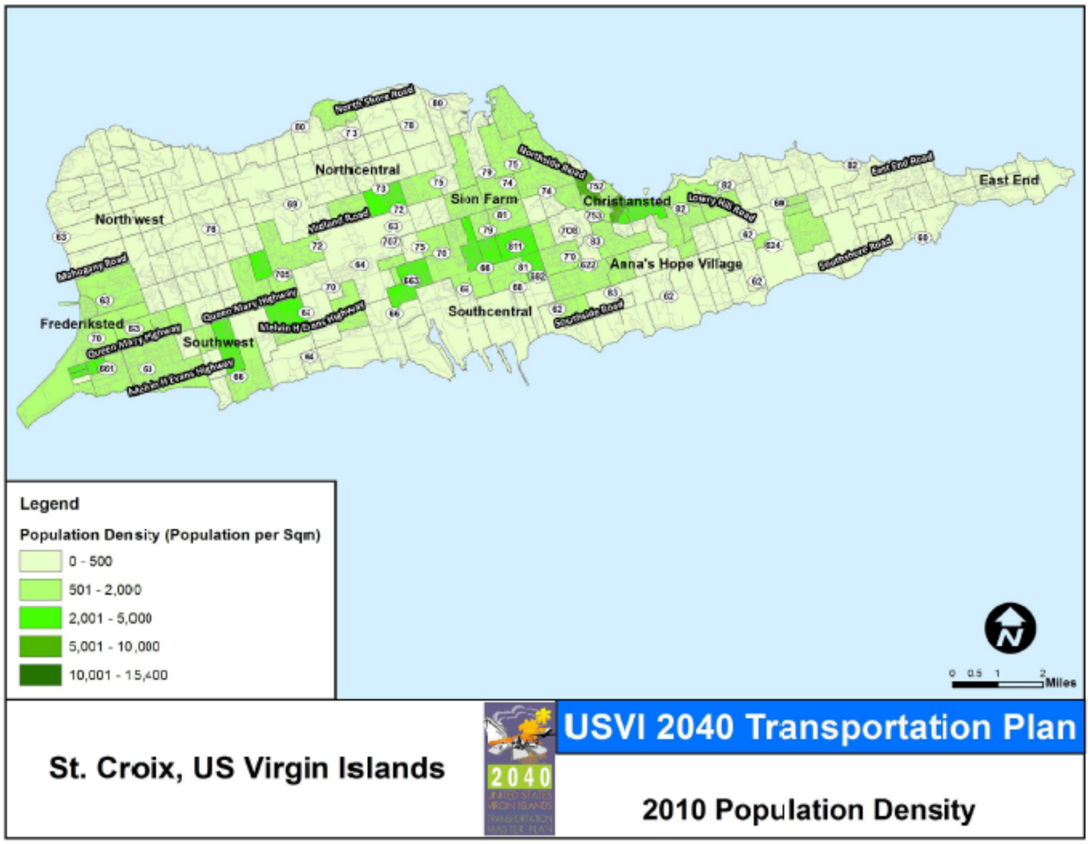


Figure A.1. Population density of St. Croix Island. (source: USVI 2040 Transportation Plan)

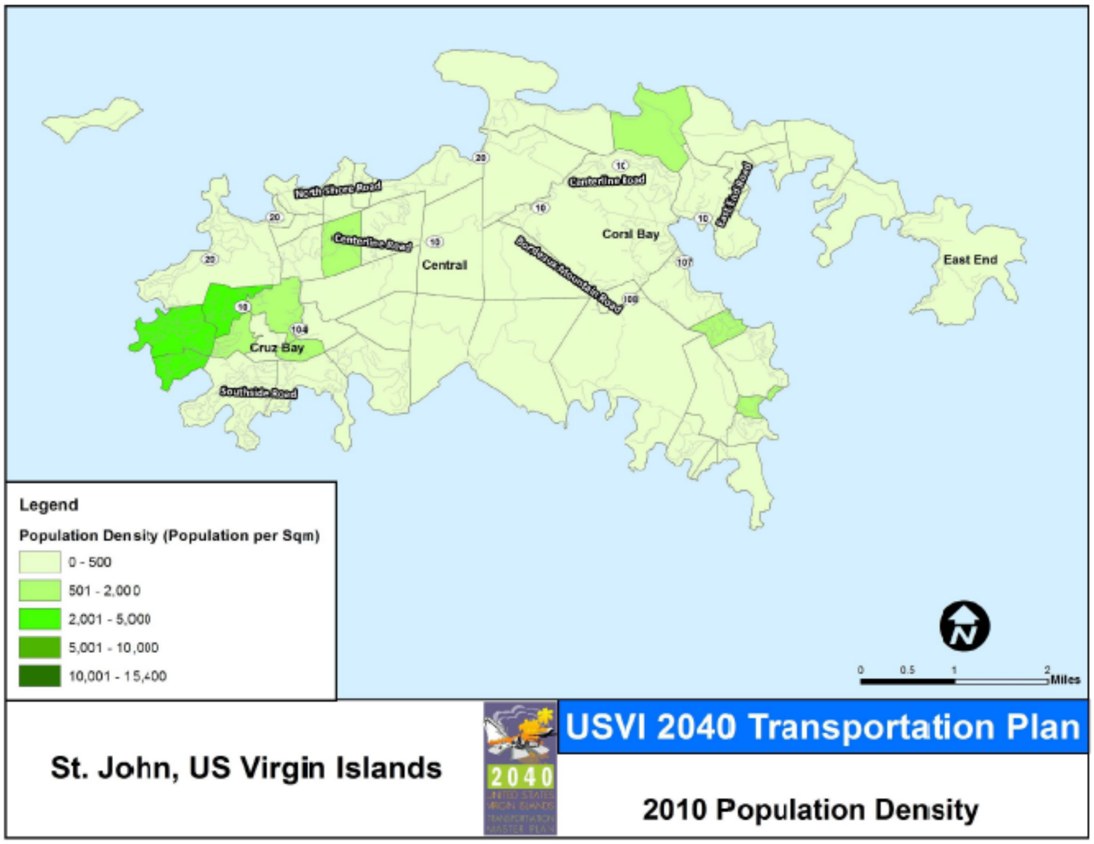


Figure A.2. Population density of St. John Island. (source: USVI 2040 Transportation Plan)

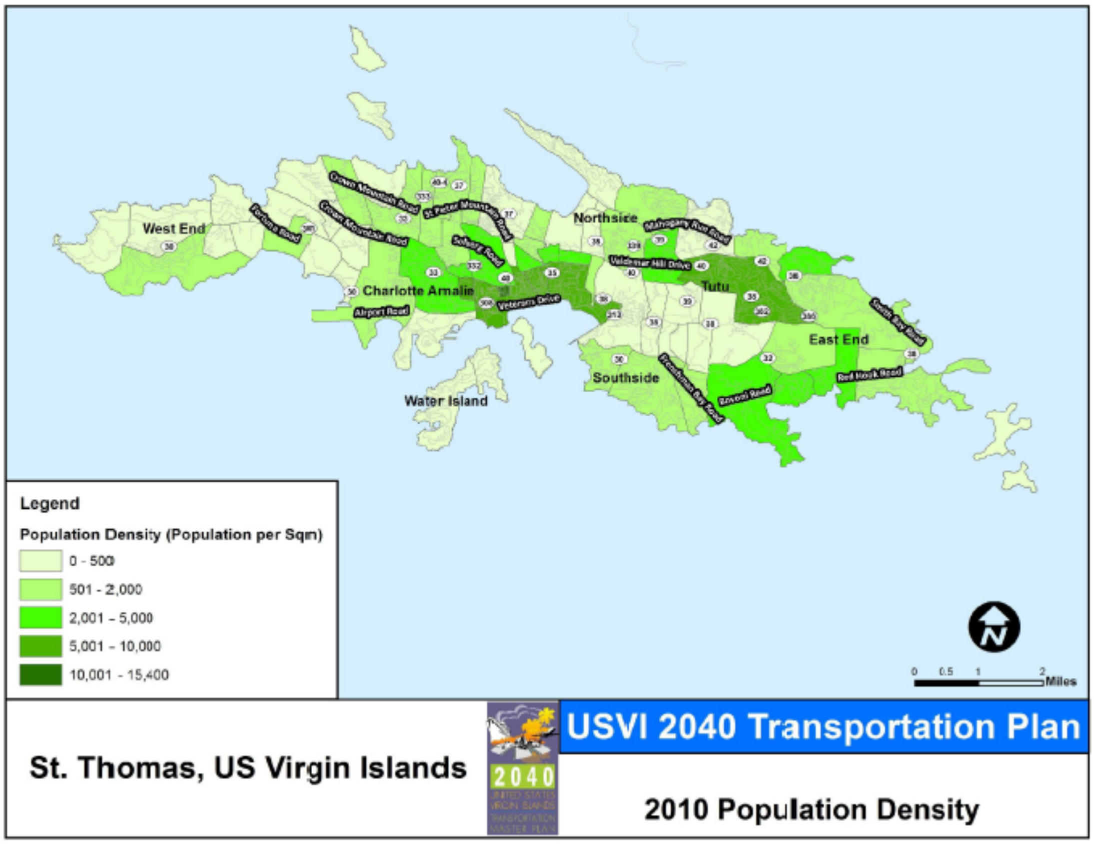


Figure A.3. Population density of St. Thomas Island. (source: USVI 2040 Transportation Plan)

A.2 Policy Guidance: Critical Infrastructure Systems

The modern study of critical infrastructure in the United States was initiated with Executive Order 13010 in July 1996, which formed the President's Commission on Critical Infrastructure Protection (PCCIP). Unlike previous efforts by the U.S. Federal Government that focused primarily on the role of infrastructure systems to support war mobilization (see Brown 2006, for a brief history), the PCCIP was specifically tasked to look at the challenges associated with growing interdependencies, especially the growing use of the Internet to interconnect previously disparate systems. As noted in its final report (p.24), "The security, economic prosperity, and social well being of the US depend on a complex system of interdependent infrastructures. The lifeblood of these interdependent infrastructures is energy" (President's Commission on Critical Infrastructure Protection 1997).

Current U.S. national policy on critical infrastructures was established by the Presidential Policy Directive (PPD) on Critical Infrastructure Security and Resilience (known as PPD-21), issued in February 2013. Following previous policy, PPD-21 designates the Department of Homeland Security (DHS) as the lead agency to "provide strategic guidance, promote a national unity of effort, and coordinate the overall Federal effort to promote the security and resilience of the Nation's critical infrastructure." The primary coordinating document for DHS is the National Infrastructure Protection Plan (NIPP), last revised in 2013 following PPD-21, with the DHS Office of Infrastructure Protection serving as the lead agency for implementation coordination. Whereas PPD-21 divides the various critical infrastructure systems and assets into 16 sectors, the NIPP designates a Sector Specific Agency with the lead coordinating function (e.g., the Department of Energy is the lead coordinating agency for the Energy sector). The NIPP also identifies a variety of Sector Coordinating Councils, Government Coordinating Councils, regional consortia, and other information sharing organizations for each of the sectors. Also issued in February 2013 was Executive Order 13636: Improving Critical Infrastructure Cybersecurity, which calls on the Federal Government to coordinate with infrastructure owners and operators to improve cybersecurity information sharing and best practices.

In parallel to policy focused on critical infrastructure is PPD-8, National Preparedness, issued in March 2011, which is "aimed at strengthening the security and resilience of the United States through systematic preparation for the threats that pose the greatest risk to the security of the Nation, including acts of terrorism, cyber attacks, pandemics, and catastrophic natural disasters." PPD-8 designates DHS with the overall responsibility "for coordinating the domestic all-hazards preparedness efforts of all executive departments and agencies, in consultation with State, local, tribal, and territorial governments, nongovernmental organizations, private-sector partners, and the general public; and for developing the national preparedness goal." Much of this effort is directed through the Federal Emergency Management Agency (FEMA) and is organized around several elements (The White House 2011).

- "The National Preparedness Goal states the ends we wish to achieve.
- The National Preparedness System describes the means to achieve the goal.
- National Planning Frameworks and Federal Interagency Operational Plans explain the delivery and how we use what we build.
- An annual National Preparedness Report documents the progress made toward achieving the goal.
- An ongoing national effort to build and sustain preparedness helps us maintain momentum."

At the operational level, FEMA follows several published frameworks, organized around five areas for mission preparedness: prevention, protection, mitigation, response, and recovery. For example, the National Disaster Recovery Framework (NDRF) specifically identifies several Recovery Support Functions (RSFs), each listed here with their associated lead agency:

- Community Planning and Capacity Building RSF [FEMA];
- Economic RSF [U.S. Department of Commerce];
- Health and Social Services RSF [U.S. Department of Health and Human Services];
- Housing RSF [U.S. Department of Housing and Urban Development];
- Infrastructure Systems RSF [U.S. Army Corps of Engineers]; and
- Natural and Cultural Resources RSF [U.S. Department of Interior].

This technical report is part of a broader research project that supports FEMA's Infrastructure Systems RSF, for which "[t]he goal of the recovery process is to match the post-disaster infrastructure to the community's projected demand on its built and virtual environment... The Infrastructure Systems recovery effort is first and foremost about maintaining continuous customer service" (U.S. Department of Homeland Security 2016, p.31).

A.3 About the Naval Postgraduate School

The Operations Research (OR) Department at the Naval Postgraduate School (NPS) has been studying the operation of critical infrastructure for more than 30 years. OR is a discipline that originated during World War II, and since then has developed into a broad science of helping people and organizations make better decisions using mathematical models, statistical analyses, simulations, and other analytical reasoning to understand and improve real-world operations. Militaries all over the world use OR at the strategic, operational, and tactical levels (see the Military Operations Research Society, www.mors.org), but OR is even more prevalent in the commercial world (see the Institute for Operations Research and the Management Sciences, www.informs.org). NPS has the oldest OR instructional program in existence, dating back to 1951.

The techniques used at NPS to study critical infrastructure were originally motivated by the question: *What parts of an infrastructure should we target to achieve a certain effect?* Within the Department of Defense, this is often known as effects-based targeting. Adversarial models of this type are very effective at identifying the dependencies between infrastructure components that are critical to their continued operation, and we use them to assess the vulnerability of infrastructure systems to both deliberate threats (e.g., terrorists, sabotage, vandalism) as well as non-deliberate hazards (e.g., extreme weather, engineering failure, accidents). In particular, we use a combination of game theory and large-scale systems modeling to identify selected components that disrupt system function in the ‘worst’ possible way. We can use the same basic framework to answer the additional question: *How should we invest limited resources to make our infrastructure resilient to disruption?* For example, should we ‘harden’ specific system components, or add redundancy, or expand capacity, or build new infrastructure? A general introduction to the mathematics and modeling are available from Brown et al. (2005) and Alderson et al. (2014).

The focal hub for activity related to critical infrastructure assessment is the NPS Center for Infrastructure Defense (CID, www.nps.edu/cid). Researchers at the CID have collectively performed more than 100 case studies on a variety of infrastructure systems including

- electric power (Salmerón et al. 2011, 2012, 2018);
- fuel storage and distribution (Ileto 2011; Burton 2013; Long 2013; Montgomery 2013; Rodgers 2015; Beaumont 2017);

- port operations (Delacruz 2011; Alderson et al. 2012; Mintzer 2014; Wenke 2015);
- road transportation (Alderson et al. 2017);
- telecommunications (Crain 2012); and
- evacuation (Langford 2010; Yuhas 2011) and emergency response (McCall 2006; Heidtke 2007; Farlow 2011).

Of particular interest for this project is the interdependence of critical infrastructure systems (e.g., Dixon 2011), and the way in which a failure in one system can affect others (e.g., Dickenson 2014; Ruether 2015).

The NPS Energy Academic Group (EAG) serves as the Navy's center of excellence for the study of energy-related issues across a variety of disciplines. The EAG's primary focus is graduate-level education of the future leaders of the Navy and Marine Corps. The EAG delivers educational programs via both in-residence and distance learning programs, as well as through short courses and training programs in energy security all over the world (see www.nps.edu/eag for details). The EAG also coordinates the highly diverse and interdisciplinary energy-related research programs at NPS, much of which involves faculty and students from multiple subject areas. Finally, the EAG also leads a variety of outreach activities, which include developing energy partnerships among the DOD, U.S. Government, Academia, Industry, NATO Allies, and International Partners/Military. The EAG actively explores educational and research partnerships across the full spectrum of DOD and U.S. government-related organizations, such as FEMA and DOE, and includes workforce development, stakeholdership in non-NPS academic energy curricula, and exercise support for DOD and NATO energy wargames.

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