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Resilience Analysis of Potable Water Service after Power Outages in the U.S. Virgin Islands

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Abstract

The two Category-5 hurricanes that impacted the United States Virgin Islands in 2017 exposed critical infrastructure vulnerabilities that must be addressed. While the drinking water utility has first-hand knowledge about how the hurricanes affected their systems, the use of modeling and simulation tools can provide additional insight to aid investment planning and preparedness. This paper provides a case study on resilience analysis for the island's potable water systems subject to long term power outages. Power outage scenarios help quantify differences in water delivery, water quality, and water quantity during and after the disruption. The analysis helps illustrate important differences in system operations and recovery time across the islands. Results from this case study can be used to better understand how the system might behave during future disruptions, provide justification for investment, and provide recommendations to increase resilience of the system. The analysis framework can also be used by other utilities to explore vulnerability to long term power outages.

Introduction

In 2017, the United States Virgin Islands (USVI) were impacted by two Category-5 hurricanes within a two-week period. On September 6th, Hurricane Irma made an indirect hit on St. Thomas (STT) and St. John (STJ); shortly afterward, Hurricane Maria made an indirect hit on St. Croix (STX) on September 20th (USVI Hurricane Recovery and Resilience Task Force 2018). The two storms caused such significant damage to critical

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infrastructure systems providing energy, water, transportation, telecommunications, and healthcare that recovery and mitigation efforts continue over four years later. For the water infrastructure, the aftereffects from the storms continue as evidenced by an increase in water main breaks. The storms have revealed that USVI critical infrastructure is vulnerable to a wide range of natural and human-induced disasters, including earthquakes, wildfires, floods, drought, contamination, and cyber-attacks (Alderson et al. 2018). In response, federal, territorial, and local stakeholders are leading broad efforts to develop infrastructure operations, upgrades, and plans to improve the resilience of the USVI's infrastructure.

The USVI territory is comprised of three primary islands: STT and STJ in the northern region of the territory and STX forty miles south of STT. The USVI Water and Power Authority (VIWAPA) owns and operates two potable water systems serving territorial communities, one on STT that connects to STJ through an undersea pipeline (STT-STJ), and one on STX (CDR Maguire 2019). Irma and Maria impacted the short and long term operations and management of these systems. While the physical components of the water system remained largely intact after each storm, blackouts caused by the hurricanes shut down pumping stations across all islands (Alderson et al. 2018). Lack of pumping power led to water outages across the entire territory for weeks (Bunn 2018; Wille 2019). Motivated by these cascading impacts of the power infrastructure on the potable water system, this paper focuses on the effect of long-duration, blackout-induced pumping outages on the water system's performance.

Resilient infrastructure has the ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event, as defined by the National Infrastructure Advisory Council (National Infrastructure Advisory Council 2009). In resilience analyses, long term power outages are of particular concern for drinking water utilities, given their reliance on energy for pumping and water treatment. Recent military directives, which require installations to operate during an extended utility outage (United States Army 2020), further motivated this work. While the USVI is not a military installation, island communities need to operate independently to meet energy and water needs after long term power outages. Power outages on the scale of months to a year are also of interest given concerns about "Black Sky" hazards caused by electromagnetic pulses or a cyber attack (Organek 2017). While helpful guidance is available from the United States Environmental Protection Agency and other organizations about increasing resilience to disasters, more work is needed to provide utilities with detailed site-specific methods to quantify system vulnerability. Such methods will guide resilience planning more effectively when competing resilience investments are being considered.

Drinking water distribution system resilience studies tend to focus on disruptions that occur within the purview of water utility maintenance and operations, such as pump scheduling, pipe breaks and leaks, water quality, fire flows, and supervisory control and data acquisition (SCADA) systems (Douglas et al. 2019; Kanta and Brumbelow 2013; Klise et al. 2017; Liu et al. 2020; Zhang et al. 2020). Several studies also include the effects of cascading losses within a water distribution system, as shifting operations and pressures can lead to additional breaks and customer outages (Hernandez-Fajardo Dueñas and -Osorio 2013; Pournaras et al. 2020; Shuang et al. 2020). However, major disasters like Irma and Maria show that vulnerabilities also arise from interdependencies across systems. For this reason, studies that assess the effects of interdependencies on drinking water systems, such as long term power outages on water operations or the loss of transportation infrastructure to access and repair failed assets, are of growing interest (Abdel-Mottaleb et al. 2019; Guidotti et al. 2016; Khatavkar and Mays 2018; Khatavkar and Mays 2019; Pederson et al. 2006; Rodriguez-Garcia et al. 2022; Stødle et al. 2021; Zuloaga and Vittal 2020). For example, Zuloaga and Vittal (2020) demonstrated the impacts of intermittent power supply over several weeks on co-optimized power and water system dispatch. When modeling infrastructure interdependencies, the dynamics can be modeled using feedback (e.g., Rodriguez-Garcia et al. 2022) or using exogenous constraints (e.g., Khatavkar and Mays 2019). The latter methodology is commonly used to simulate water system dependence on power and was used in this paper.

While this field of research is growing, analysis is generally carried out using synthetic infrastructure models. A recent case study for St. Kitts in the Caribbean Islands illustrated the challenges and benefits to using real systems in resilience analysis (Stødle et al. 2021). With limited data, the analysis was able to identify critical power lines needed to maintain water service across the island after a hurricane. Additionally, data from Hurricanes Dennis, Katrina, and Ivan have been used to forecast power outage duration (Nateghi et al. 2014), with wind characteristics, annual precipitation, soil moisture, and repair crew preparedness being key factors in the prediction. Case studies using real infrastructure systems and realistic disruption scenarios help to improve the understanding of complex system dynamics.

Recent advancements in simulation and analysis methods have the potential to help water utilities quantify resilience to disruptive incidents (Shuang et al. 2019). Many resilience metrics have been proposed, ranging in scope from topography to hydraulics to water quality (Khatavkar and Mays 2019; Klise et al. 2015; Shin et al. 2018). Furthermore, water service categories have been proposed that divide system functionality into water delivery, quality, quantity, and fire protection capability (Davis 2014). When conducting resilience analysis, the use of multiple metrics and service categories can increase system understanding.

The purpose of this paper is to provide a case study on how to assess the resilience of STT-STJ and STX potable water systems subject to long term power outages. Several power outage scenarios were simulated to track system performance given outages at various pump stations and resilience was measured using metrics that represent different water service categories. The case study provides a simulation and evaluation framework to quantify disruptions to drinking water distribution systems due to blackouts and demonstrates the importance of considering measures from both the customer and operator perspectives. Quantifying the ability of the VIWAPA water distribution systems to function after disruptions provides vital information to disaster managers, and helps prioritize investment strategies that improve design, operations, and upgrades.

USVI Water Distribution Systems

The USVI territory and VIWAPA potable water systems have several unique features that have motivated this case study. First, unlike many systems operated in the continental United States that can be connected or are in close proximity to other water utilities, USVI water distribution systems are isolated, island systems. Because of this isolation, the resilience analysis is more straightforward since the USVI water distribution systems have clear physical, operational, and management boundaries. However, their isolation could make them more vulnerable to disasters. In many urban drinking water distribution systems, the loss of a pump station could be mediated by equipment and pumping from an interconnected utility or by accessing water from another source. USVI water distribution systems do not have the ability to access water when pumping becomes unavailable due power or equipment failures. For that reason, quantifying the length of time that these systems can continue to provide potable water after a blackout is critical for guiding emergency response. This was especially apparent after the 2017 hurricanes as support from nearby islands, like Puerto Rico, was unavailable since they were also affected by the storms.

Second, USVI potable water systems are complicated due to the widespread adoption of rainwater catchment systems. USVI communities have a long history of relying on rainwater catchment for daily water, and, until recently, territorial law required all buildings to include a water storage cistern. As a result, many water customers can choose to access water from the VIWAPA water distribution system, or from other sources including rainwater, water truck haulers, private producers, and individual accounts with VIWAPA (Borgdorff 2020). These sources of water could act as a buffer on the system and provide an alternate source of water after a hurricane. Unfortunately, the alternate sources of water could also be unavailable after a hurricane due to damage, contamination, or lack of power for pumping. On STT-STJ, approximately 33% of the population receives water from VIWAPA, while on STX approximately 44% the population receives water from VIWAPA. Water service from non-VIWAPA sources generally occur in higher elevation regions which are not included in the water distribution system or model. While VIWAPA provides less than half of the water services across the islands, the water use has a large impact on the community as it includes residential, commercial, and industrial demands. The following case study of the STT-STJ and STX systems provides a starting point for the assessment of interacting water sources and distribution methods. A brief description of the USVI water distribution systems and models are provided below.

St. Thomas and St. John Water Distribution System and Model

STT and STJ are neighboring islands in the territory, with Charlotte Amalie on STT being the main population center. The populations of STT and STJ were 42,261 and 3,881, respectively, based on the 2020 census (US Census Bureau 2020). The water distribution system served 15,400 people as of 2021 (D. Gregoire, Personal communication, 2021). Water is produced at one reverse osmosis facility on the west end of STT near the airport and then stored in three tanks. The pumps are located near the reverse osmosis facility supply water to the distribution system, which includes twelve additional pumps and five tanks. The STJ and the eastern half of STT are gravity-fed from a tank located at the center

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of STT. STT and STJ water systems are connected via a submarine pipe extending from the eastern shore of STT to the western shore of STJ. The reverse osmosis facility produces 1.9 million gallons of water per day on average. The total storage tank capacity is 37 million gallons, giving the system approximately 19 days of stored water. The network has an average operating pressure of 73 psi and water losses from leaks are estimated to be around 14% of the total water supplied to the system (CDR Maguire 2019).

The water distribution network model for the STT-STJ system used in this case study is based on the STT and STJ models developed for the VIWAPA Master Plan (CDR Maguire 2019). Several updates, guided by water utility conversations and data, were made to the VIWAPA Master Plan models. For a resilience analysis, a model should be able to reflect current normal operating conditions and respond to stress conditions. While additional calibration would improve model accuracy, the updates were an important step to ensuring that the analysis results reflected system configuration and behavior.

The resulting model contained 160 junctions, 1 reservoir (i.e., the reverse osmosis facility), 6 tanks, 181 pipes, 7 pumps, and 8 valves. Of the 160 junctions, 54 had non-zero demand. The pumps were grouped into four pump stations. Two pump stations were located near the reverse osmosis facility in Charlotte Amalie, one was located at the center of STT west of the central STT tank, and one was located on STJ. The general direction of water flow was from the west (the reverse osmosis facility on STT) to the east (STJ). Fig. 1 illustrates the STT-STJ model layout, system components (tanks, reservoir, pump stations), and island regions used to describe results.

The pump stations were used in the power outage case study, which explored three power outage scenarios. The "system-wide power outage" cut power to all pumps, the "source power outage" cut power to the two pump stations near the reservoir, and the "distribution power outage" cut power to the two pump stations located within the distribution system (one located in the center of STT and one on STJ). For the system-wide and source power outages, the pipes from the reverse osmosis facility were closed, effectively eliminating water production. For the purpose of reporting analysis results, the two island system was divided into three regions: East, Central, and West. This helped identify regional differences in water service.

St. Croix Water Distribution System and Model

STX is the largest island in the territory and includes two primary cities: Frederiksted and Christiansted. The population of STX was 41,004, based on the 2020 census (US Census Bureau 2020). The water distribution system serviced 18,088 people as of 2021 (D. Gregoire, Personal communication, 2021). Water is produced in two reverse osmosis facilities in Christiansted and stored in a nearby tank. A pumping station then supplies water to the distribution system, which includes two additional pumping stations and six tanks. The system is gravity-fed from a tank located in the center of the island. The reverse osmosis facilities average 2.9 million gallons per day. The total storage tank capacity is 23 million gallons, giving the system approximately eight days of stored water. The system has an average operating pressure of 55.6 psi. Water loss is estimated to be as high as 40% with numerous leaks on the west end of the island leading to inadequate supply in Frederiksted.

The system also has high water age and low residual chlorine on the west side of the island (CDR Maguire 2019).

The water distribution network model for the STX system used in this case study is based on the model developed by Wille (Wille 2019). This model has higher spatial resolution than the model for the VIWAPA Master Plan (CDR Maguire 2019). Several updates were made to the Wille model for this analysis, guided by conversations with the water utility, utility data, and information from the VIWAPA Master Plan. As with the STT-STJ model, additional calibration would improve model accuracy for the STX model. Nevertheless, model updates are an important step to complete before resilience analysis is conducted.

The resulting model contained 710 junctions, 1 reservoir (i.e., the reverse osmosis facilities), 7 tanks, 871 pipes, 8 pumps, and 16 valves. Of the 710 junctions, 199 had non-zero demand. The pumps were grouped into three pump stations. One pump station was located near the reverse osmosis facilities in Christiansted, while the other two were located in the center of the island (one to the north and one to the south). The general direction of water flow was from the east (where the reverse osmosis facilities are located in Christiansted) to the west (Frederiksted). Fig. 2 illustrates the STX model layout, system components (tanks, reservoir, pump stations), and island regions.

The pump stations were used in the power outage analysis and the same naming conventions from the STT-STJ analysis were used to describe the pump station outages and regions of the island. The “system-wide power outage” cut power to all pumps, the “source power outage” cut power to one pump station near the reservoir, and the “distribution power outage” cut power to the two pump stations located within the distribution system (one on the north and one on the south side of the system). For the system-wide and source power outages, the pipes from the reverse osmosis facilities were closed, effectively eliminating water production. Analysis results were divided into three island regions: East, Central, and West.

Methods

Given the networks’ strong reliance on pumping to meet water needs across the islands, this analysis sought to quantify how water service would be disrupted following long term power outages. The following section describes the power outage simulations and metrics.

Power Outage Simulations

The system-wide power outage, source power outage, and distribution power outage scenarios were simulated using the Water Network Tool for Resilience (WNTR) (Klise et al. 2020). WNTR is a Python package designed to simulate and analyze resilience of water distribution systems. For this case study, the software was updated to better define power outages at pump stations and compute metrics that track the impact on water service over time. Recent updates in EPANET (Rossman et al. 2020; Salomons et al. 2018), which have also been integrated into WNTR, facilitate pressure-dependent demand (PDD) modeling. The updated EpanetSimulator within WNTR (which uses EPANET 2.2) was used for this analysis. The PDD model is critical for power outage analysis to accurately model low pressure conditions when expected demands might not be met. Note that the use of PDD with the EpanetSimulator in WNTR is equivalent to using EPANET with pressure driven analysis (called PDA within EPANET). WNTR also includes an application programming interface (API) which facilitates custom analysis directly within the Python environment. This includes the ability to add and prioritize controls for each power outage, change initial conditions (such as tank level and water age), convert simulation results to metrics like water service availability, and create graphics.

The long term power outage scenarios were defined using the following assumptions:

- The power outage lasted for four weeks and backup generation was not available. A 4-week outage duration was selected to quantify system behavior after exceeding the stored water reserves in the system. For these systems, all tank reserves were drained after a simulated 4-week power outage. This was longer than the stored water reserves (19 days for STT-STJ) because water consumption was limited by low pressure conditions during the simulated outage.
- The power outage started when tanks were near full capacity. Real power outages could occur at any time, and could happen before a system recovers from a previous disruption, as was the case when the hurricanes hit the USVI within a two-week period. Future analyses could include this type of back-to-back disruption, and study the impact of tank storage on system resilience.
- Water consumption did not change after the outage. After a hurricane, water consumption could decrease if people are displaced or increase if alternate sources of water are no longer available and people need to rely more on the water utility. For this reason, normal water consumption was used as a baseline. Because the hydraulics are pressure-dependent, normal water consumption was reduced due to low pressure conditions during the simulated outage.
- Pipes, pumps, tanks, valves, and water treatment facilities were not damaged by the hurricane or power outage. Damaged components could be included in the analysis, in the form of leaks, changes in operations, and reduced water quantity. In this analysis, the infrastructure was not damaged and pumps could be turned on immediately once the outage was over.
- Water quality was not affected by low pressure conditions. Low pressure conditions could lead to contaminant intrusion, which might alter consumption and cause boil water alerts. Water quality analysis could be included in future analyses.
- Water hammer was not a concern when restarting pumps. Transient hydraulic simulation could be used in future analyses to include the effect of water hammering on pipes (Xing and Sela 2020).

For each scenario, the power outage started after two weeks of normal operations. The pumps were then turned off for four weeks, then turned back on. When power was restored, the pumps ran continuously or until their associated tanks reached the maximum level. An additional four weeks after the outage were simulated to see how the system returned to normal operations. During each outage, water was allowed to flow from tanks until the tanks were empty, and past the de-powered pumps into the system. The impact of shorter duration outages could be approximated by the single long-duration outage scenario. While simulation results up to the time the power was restored were the same, recovery times would differ. Once the tank reserves were depleted, there was no further impact from longer duration outages.

While the case study used normal water consumption throughout the simulation, lower and higher consumption levels were explored as part of the analysis. Water consumption and the time until critical water service thresholds were crossed were inversely related. In high water consumption scenarios, water service reduced more quickly, while in low water consumption scenarios, water age (and therefore water quality) became an issue.

When defining power outage scenarios or scenarios that represent other disruptive incidents, it is important to define network model controls in a way that clearly identifies the priority order. Water network models commonly include controls prioritized based on the order in which they are added to the model. While this might suffice during normal operating conditions, this might not be the desired prioritization during a power outage. For example, a pump that has been shut off due to power failure cannot be turned on to fill a tank until power is restored. For this reason, WNTR now includes the ability to define a priority for each control in the system (in EPANET terminology, this converts controls to rules) and to easily define power outage controls with a start time, end time, and priority.

Metrics

The following metrics were used to describe how the system functioned during the power outage scenarios: modified resilience index, water service availability, water age, and tank capacity. The modified resilience index and water service availability were each used as separate water delivery service indicators, water age was used as a water quality service indicator, and tank capacity was used as a water quantity service indicator. Each metric was reported as a system-averaged time series, and as a region-averaged time series using the East, Central, and West regions shown in Figs. 1 and 2. In this analysis, the metrics were computed for each node (non-zero demand junction or tank) and then averaged over the system or region. By contrast, weighted averages could also be computed within each system or region. The way in which the averages were computed here emphasizes the impact of water service to individual junctions and tanks.

Modified resilience index (MRI) is the ratio of surplus energy (total energy minus required energy) to required energy, computed at each junction and timestep (Jayaram and Srinivasan 2008). The total energy was computed from the simulated junction pressure, and required energy was computed from the 30 psi required pressure used for the PDD simulations. Pressure was converted to energy using junction elevation, water density, and the specific weight of water. An MRI value of 0 means that the system is operating at its required energy conditions. Positive values mean that there is a surplus, while negative values indicate a deficit. The values can be over 1, but cannot be below −1 if elevation and pressure are positive.

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Water service availability (WSA) is the ratio of simulated delivered demand to the expected demand, and is sometimes referred to as the fraction of delivered volume (Ostfeld et al. 2002). WSA is computed at each junction and timestep and falls between 0 and 1. Pressures drops in the system due to inadequate pumping can cause expected demands to be unmet, leading to WSA values below 1. When no water can be delivered, WSA equals 0.

Water age is the amount of time water spends in the network, starting from the time water enters from a reservoir or source node (Rossman et al. 2020). In this analysis, water age was computed in WNTR using the EPANET water quality simulation options and was used as a proxy for water quality. When modeling water age, it is important to properly initialize the simulation to establish a normal baseline water age in all parts of the system instead of initializing the entire system with a water age of 0. Water age was initialized using a base scenario that modeled normal conditions (no outage) for seven weeks. The water age and tank levels at the end of the base scenario were used to initialize the power outage scenarios. The difference in water age between the base scenario (i.e., normal conditions) and each power outage scenario was used to estimate changes in water quality. This metric was quantified for each junction and timestep. A value of 0 implies that the water quality in the system has no change after a power outage. A value greater than 0 implies possible reductions in water quality. A value less than 0 implies that the system flushes new water through the system at a faster pace than normal. This would also indicate a change from normal water quality.

Tank capacity is defined as the ratio of current water volume stored in tanks to the maximum volume of water that could be stored. The current water volume is a function of simulated tank levels. This metric is computed at each tank and timestep and ranges between 0 and 1. A value of 1 indicates that tank storage is maximized, while a value of 0 means no water is stored in the tank. The STT-STJ and STX systems both had average tank capacities around 0.9 under normal conditions.

Summary statistics for the metrics included the minimum MRI, minimum WSA, maximum difference in water age, and minimum tank capacity. Additionally, for each metric, the time in which that metric reached a specific threshold was extracted. Thresholds were selected to quantify system decline and differentiate resilience between regions. The threshold for MRI was set to 0 (no surplus energy), the threshold for WSA was 0.5 (half of expected demands were delivered), the threshold for the difference in water age was 20 (the water was 20 days older compared to a simulation without a power outage), and the threshold for tank capacity was 0.2 (20% of tank storage was full). Each threshold was intended to be a leading indicator of system failure for the utility and these thresholds could be modified to assess different levels of system decline. In each case, the elapsed time was measured from the start of the outage.

In addition to the metrics described above, two recovery times were assessed: time to initial recovery and time to full recovery. Time to initial recovery quantifies system recovery from the consumer perspective and is related to the time needed for WSA to stabilize close to pre-disaster conditions and MRI to show a surplus. Time to full recovery quantifies system recovery from a utility operations perspective and is related to the time required to refill tanks and return the system to pre-outage conditions after the disaster. Water age could also be used to define initial or full recovery. However, the difference in water age metric might not be the best proxy for water quality in this regard. Note that since water is simulated as an incompressible fluid, the recovery times are conservative; when pumping restarts and the system begins to re-pressurize, the pressure wave moves through the system instantaneously.

Results

The following section includes summary statistics and time series of MRI, WSA, difference in water age, and tank capacity from each power outage scenario along with a description of system operation during and after each outage. All simulation results are presented as a 24-hour moving average to remove daily fluctuations and make the results easier to interpret.

St. Thomas and St. John Power Outage Scenarios

The three power outage scenarios were simulated using the STT-STJ network model. Table 1 includes summary statistics for each scenario based on system averages. The MRI metric, used to quantify water delivery, fell below the critical threshold within 11.5 to 17.1 days for the system-wide and source power outages, respectively. The WSA metric, also used to quantify water delivery, had a similar response and fell below its critical threshold within 12.0 and 17.2 days for the system-wide and source power outage, respectively. The distribution power outage was able to maintain water delivery based on MRI for the entire four week outage, and WSA stayed above the critical threshold for nearly the entire outage (26.0 days). The similarity in MRI and WSA was expected given their reliance on system pressure. Difference in water age (a metric inversely related to water quality) rose above the critical threshold within 9.0 to 17.0 days for the source and system-wide power outages, respectively, while the distribution power outage maintained water age below the critical threshold for the entire four week outage. Tank capacity, used to quantify water quantity, fell below the critical threshold within 14.0 to 19.2 days for the system-wide and distribution power outage, respectively, and tank capacity remained above the threshold for nearly the entire source power outage (26.3 days).

While the time to initial recovery was very fast for all scenarios (within 2 days), the time to full recovery was very long for the system-wide and source power outages. In both cases, full recovery was not reached before the end of the simulation which was set to 28 days after power was restored. The long recovery time was caused by the large storage capacity and long fill time for tanks located near the reverse osmosis facility. While these tanks served as a buffer for the system during the disaster scenario, the long recovery time left the system vulnerable to successive power outages.

Fig. 3 includes the time series for MRI, WSA, difference in water age, and tank capacity for the entire system average, along with average values for the East, Central, and West regions of the two island system. This figure helps illustrate the importance of specific pump stations and tanks to retain water service in different parts of the island after a disaster. Before the power outage, STJ (East) had the lowest MRI, while western STT (West) had the highest. This indicated that the system contained the lowest energy surplus in the East, furthest downstream of the source pumping, in an area which was known to have daily oscillations in low pressure conditions. Because of this, WSA for the STJ (East) region was below 1 even before the power outage was simulated.

In general, the West region was immediately impacted by the source power outage, gradually by the system-wide power outage, and not at all by the distribution power outage. The East region was immediately impacted by the system-wide and distribution power outages, but almost maintained service through the source power outage. The response to the power outages in the Central region was generally bounded by the system behavior in the East and West regions. While the source and system-wide power outages had similar impacts on system behavior, the order in which tanks drained and water service was lost differed. With the source power outage, the distribution pumps continued to operate and maintain WSA in the Central and East regions for an extended period of time. The summary metrics were very similar for both scenarios, with minimum WSA and tank capacity both going to 0 within 23–26 days. Both scenarios had fast initial recoveries (the time it takes to restore water service), but slow full recoveries (the time needed to refill tanks). More than 28 days were needed to refill tanks. The additional storage in the STT-STJ system extended water service after the outage, but required additional time to fully recover.

St. Croix Power Outage Scenarios

The power outage scenarios were duplicated on the STX network model. Table 2 includes summary statistics for each scenario based on system averages. The STX network model had a shorter time to failure than STT-STJ in the system-wide and source power outages, but was able to maintain service throughout the distribution power outage. Water delivery, based on the MRI metric, fell below the critical threshold within 5.6 to 6.6 days for the system-wide and source power outages, respectively. The WSA metric followed a similar trend, falling below the critical threshold within 8.8 to 10.5 days for the system-wide and source power outages, respectively. Both the MRI and WSA metrics remained above their associated critical thresholds for the entire four week outage for the distribution power outage. As noted in the results for STT-STJ, similarities in MRI and WSA were expected. The difference in water age rose above the critical threshold within 9.0 to 9.6 days for the source and system-wide power outages, respectively, while the distribution outage did not exceed its threshold. Water quantity (based on tank capacity) fell below the critical threshold within 6.1 to 9.1 days for the system-wide and distribution power outages, respectively, but water quantity remained above the threshold for the entire outage for the source power outage. Compared to the STT-STJ recovery, the initial recovery for STX was slightly longer for all power outage scenarios, but full recovery was quicker across all scenarios.

Fig. 4 includes the time series for MRI, WSA, difference in water age, and tank capacity for the entire system average, along with average values for the East, Central, and West regions of the island. Unlike the STT-STJ model, expected water demands were almost all met during normal operations prior to the outages, with WSA close to 1 in the first 14 days of the simulation. Fredericksted (West) included a few junctions with low pressure conditions, which dropped WSA to slightly below 1. WSA was above 1 for a couple of timesteps due to brief numerical instability in the simulation.

As with the STT-STJ power outage scenarios, the system-wide and source power outages were similar; however, the order in which tanks drained and the regions lost water service was different. When the distribution pumps were operating (source power outage), WSA remained high in the Central and West regions for an extended period of time. In both system-wide and source outage scenarios, WSA and tank capacity reduced to zero between 14.8 to 18.0 days after the start of the outage. The recovery periods of both scenarios were quite similar, with the initial recovery taking 3.0 days and the full recovery taking 6.7 days. Unlike the STT-STJ simulations, STX was able to fully recover within the 28 days of simulated post-disaster time.

Discussion

Results quantified how the STT-STJ and STX systems led to differences in water delivery, quality, and quantity. On the surface, the STT-STJ and STX systems appeared similar, with roughly the same number of customers, reservoirs, pump stations, water regions, and operations. However, blackouts affected both systems in distinct ways. Water pressure and storage were better managed in the STT-STJ system than the STX system during system-wide power outages, as STX experienced sharp declines in MRI, WSA, and tank capacity. However, STT-STJ experienced greater increases in water age that might lead to water quality issues. While STX appeared more vulnerable to outages that included the source pump station, the STX system was capable of maintaining water service during distribution outages of four weeks. In contrast, the STT-STJ system exceeded thresholds for reductions in water services in the Central and East regions during distribution outages.

These results could help provide justification for VIWAPA investment planning and preparedness for resilience to future storms. For the STT-STJ system, the primary concerns during power outages were maintaining pressure in the Central and East regions and ensuring proper water quality in the West. These results indicated that backup generators and uninterruptible power supplies that ensure pump operations during hurricanes were more critical for the distribution pump stations than the source. Follow-on analysis could look at the impact of backup generators on select pumps within the system.

Results also indicated that ensuring clean water by adding disinfectant with non-electrical equipment or providing water via trucks and bottles would be important for the West near the source pump station. For STX, the opposite was true. Distribution power outages did not lead to major water service disruptions, while source outages did. Moreover, the West region far from the source pump station experienced the greatest water age and even exceeded the thresholds during distribution outages. Thus, the STX system would benefit from backup and uninterruptible power supplies at the source pump station, and adding disinfectant or ensuring trucked and bottled water would be important for the West. Moreover, both STT-STJ and STX systems experienced significant loss of tank capacity, suggesting that more water storage was necessary to manage long-duration blackouts in both systems.

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Conclusions

The case study presented here shows the importance of hydraulic modeling for understanding system vulnerability to disruptions experienced by water utilities under extreme scenarios. This analysis demonstrates important methods and tools for measuring the impacts of long term power outages on vulnerable water distribution systems. Having detailed models and impact analyses support more effective and efficient system recovery and response planning. Additionally, the analysis helps guide immediate upgrades to failed infrastructure that mitigate future disruptions.

This type of quantitative analysis is rarely applied to real systems and disruptions. The analysis illustrates that system resilience is more complex than a single measure or metric. Pressure- and service-based metrics (i.e., MRI and WSA) provide a consumer-based view of system function, while water age and tank capacity provide a utility-based view. The analysis also highlights the reliance on power for water service in different regions of the island, illustrating that different communities are impacted by power outages in different ways. While water quantity might be the top concern in one region, water quality might be more concerning in another region. While the case study focuses on STT-STJ and STX, the simulation and evaluation framework used in this study can be used by other water utilities to quantify water service categories during long term power outages.

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Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data). This includes the VIWAPA water distribution system models.

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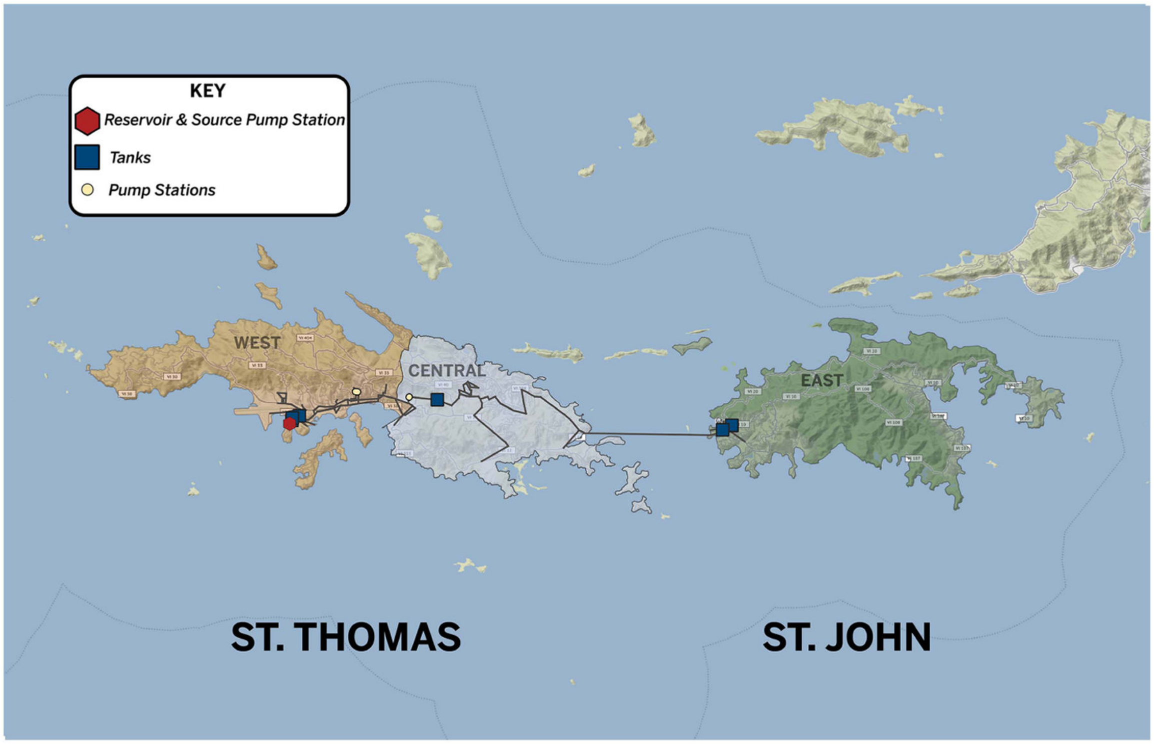

Fig. 1.
Map of STT-STJ water distribution system and island regions used in this analysis. [Map tiles by Stamen 2022, under Creative Commons-BY-3.0 license (https://creativecommons.org/licenses/by/3.0/); Data by OpenStreetMap, under ODbL.]

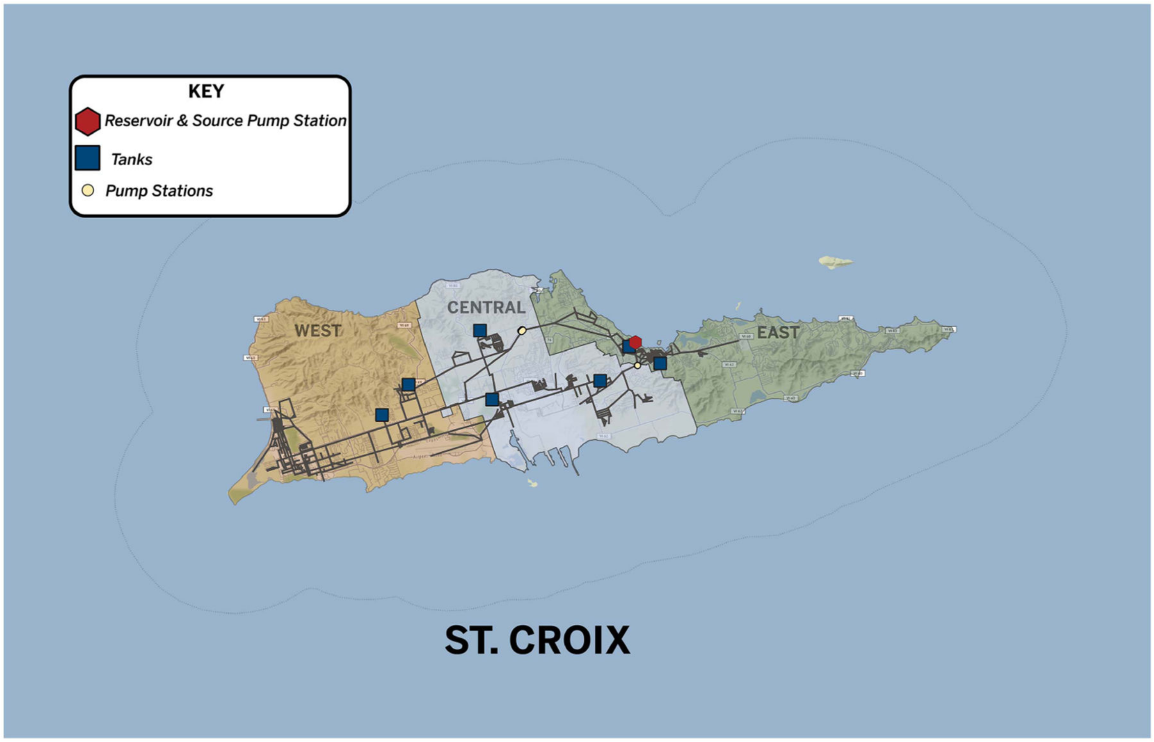

Fig. 2.

Map of STX water distribution system and island regions used in this analysis. [Map tiles by Stamen 2022, under Creative Commons-BY-3.0 license (https://creativecommons.org/licenses/by/3.0/); Data by OpenStreetMap, under ODbL.]

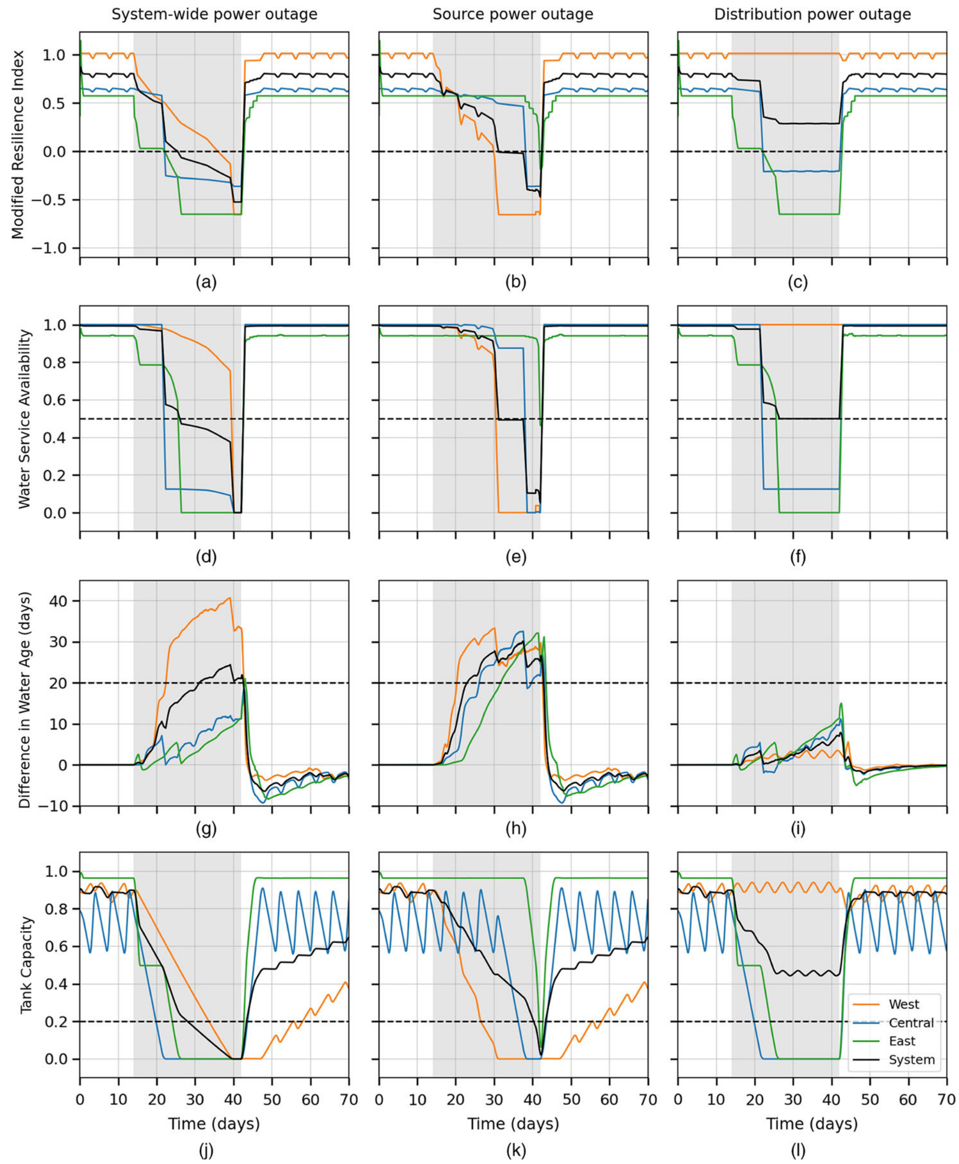

Fig. 3.

STT-STJ results showing: (a–c) modified resilience index; (d–f) water service availability; (g–i) difference in water age; and (j–l) tank capacity for the (a, d, g, j) system-wide, (b, e, h, k) source, and (c, f, i, l) distribution power outage scenarios. Each subplot shows results averaged over the East, Central, and West regions and over the entire system (legend is in subplot l). The light shaded region marks the duration of the power outage. The dashed horizontal lines indicate thresholds used in Table 1.

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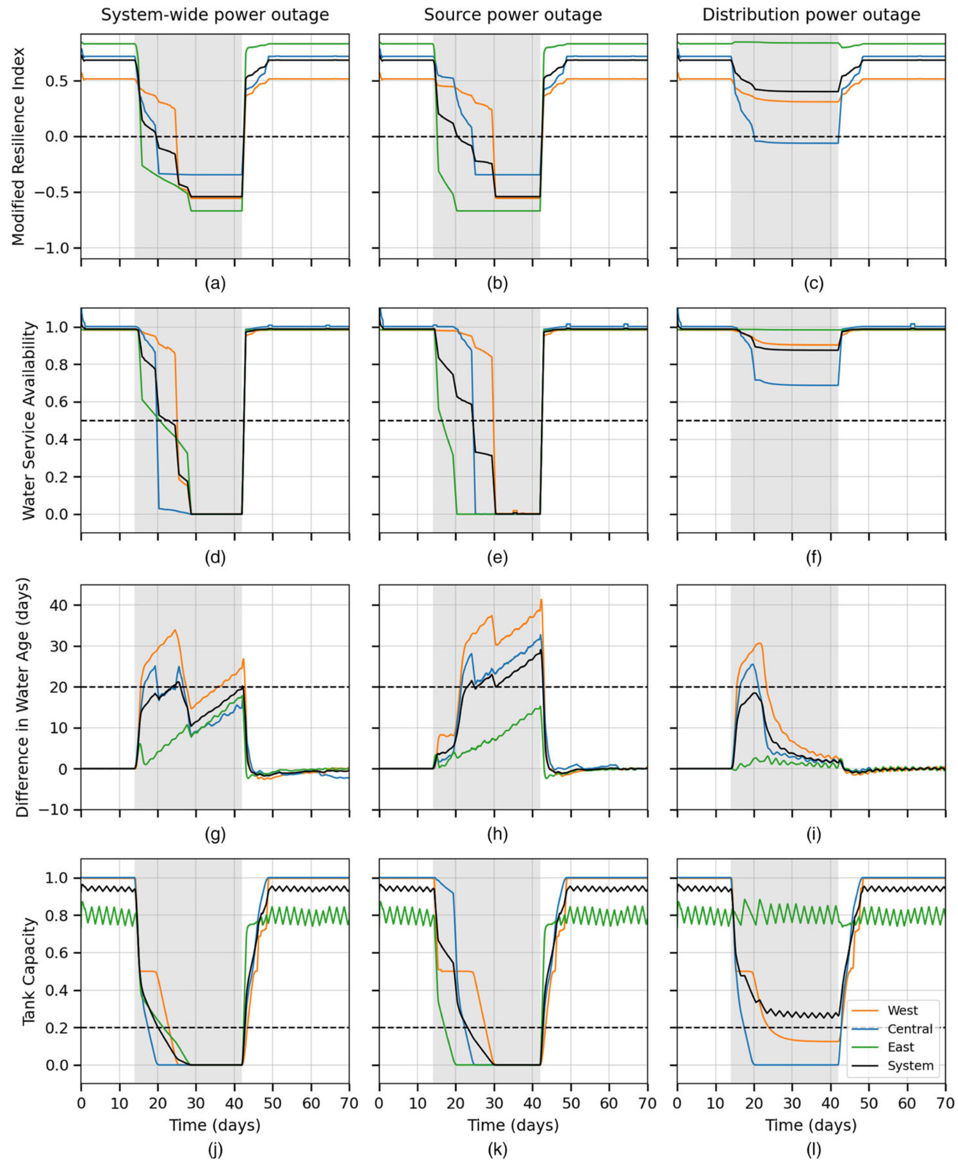

Fig. 4.

STX results showing: (a–c) modified resilience index; (d–f) water service availability; (g–i) the difference in water age; and (j–l) tank capacity for the (a, d, g, j) system-wide, (b, e, h, k) source, and (c, f, i, l) distribution power outage scenarios. Each subplot shows results averaged over the East, Central, and West regions and over the entire system (legend is in subplot l). The light shaded region marks the duration of the power outage. The dashed horizontal lines indicate thresholds used in Table 2.

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Table 1.

Summary metrics for STT-STJ power outage scenarios based on system average

Summary metric	System-wide power outage	Source power outage	Distribution power outage
Days until MRI <0	11.5	17.1	N/A
Minimum MRI	−0.53	−0.47	0.29
Days until WSA <0.5	12.0	17.2	26.0
Minimum WSA	0.00	0.05	0.50
Days until difference in water age >20 days	17.0	9.0	N/A
Maximum difference in water age	24.46	30.14	7.89
Days until tank capacity <0.2	14.0	26.3	19.2
Minimum tank capacity	0.00	0.02	0.44
Days to initial recovery	1.1	1.1	1.0
Days to full recovery	28+	28+	6.3

Note: An entry of N/A means that the metric never crossed the threshold. The entries of 28+ indicate days to full recovery extended beyond the end time of the simulation. Large capacity tanks in this system take approximately 100 days to return to full capacity.

Table 2.

Summary metrics for STX power outage scenarios based on system average

Summary metric	System-wide power outage	Source power outage	Distribution power outage
Days until MRI <0	5.6	6.6	N/A
Minimum MRI	−0.54	−0.54	0.40
Days until WSA <0.5	8.8	10.5	N/A
Minimum WSA	0.00	0.00	0.88
Days until difference in water age >20 days	9.6	9.0	N/A
Maximum difference in water age	21.21	29.11	18.50
Days until tank capacity <0.2	6.1	9.1	N/A
Minimum tank capacity	0.00	0.00	0.25
Days to initial recovery	3.0	3.0	2.4
Days to full recovery	6.7	6.7	5.9

Note: An entry of N/A means that the metric never crossed the threshold.