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Dependent infrastructure system modeling: A case study of the St. Kitts power and water distribution systems

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ABSTRACT

Critical infrastructure systems underlie the economy, national security, and health of modern society. These infrastructures have become increasingly dependent on each other, which poses challenges when modeling these systems. Although a number of methods have been developed for this problem, few case studies that model real-world dependent infrastructures have been conducted. In this paper, we aim to provide another example of such a case study by modeling a real-world water distribution system dependent on a power system. Unlike in the limited previous case studies, our case study is in a developing nation context. This makes the availability of data about the infrastructure systems in this case study very limited, which is a common characteristic of real-world studies in many settings. Thus, a main contribution of the paper is to show how one can still develop representative, useful models for systems in the context of limited data. To demonstrate the utility of these types of models, two examples of different analyses are performed, where the results provide information about the most vulnerable parts of the infrastructures and critical linkages between the power and water distribution systems.

1. Introduction

Critical infrastructures provide essential services to modern societies, and the functionality of these infrastructures are important. There has been an increase in dependencies of a given infrastructure on one or more other infrastructure systems, particularly dependencies on the power system. These dependencies are often poorly understood in practice, despite assumptions to the contrary made by academic modelers. Even when they are understood, modeling the cascading effects of failures from one system onto other systems is challenging. Many methods for modeling dependent infrastructures using network models have been developed and suggested in existing literature (e.g., [1,8,22]). Many of these papers adopt a network theoretic perspective (e.g, [7,10,17]). That is, they conceptualize a set of infrastructure networks as graphs of vertices and edges and approximate performance with one of a number of topological or connectivity-based approaches. However, LaRocca et al. [18] showed that these network theory-based approaches, while useful for generic networks, provide poor approximations of the performance of actual infrastructure systems. Despite this, relatively few detailed case studies of the modeling of real-world dependent infrastructures are published in the scientific literature (e.g. [3,6,15,16,21,23,29]). Nearly all of these are done in unique data-rich environments that are not representative of the situation faced by many infrastructure managers. Many infrastructure managers, even in developed countries, face significant data limitations, especially about dependencies on other infrastructures. In many cases, performance models (e.g., hydraulic models for drinking water systems) are out of date or have not been calibrated in many years. The main contribution of this paper is to show how real infrastructure systems involving dependencies can be modeled in low-data environments in a way that provides useful information on the performance of these systems during natural hazards.

This paper differs substantially from previous case studies in relatively data-rich areas such as the United States and Europe. We present a case study where we analyze the effect of hurricane disruptions on the performance of the power and water distribution systems of the Caribbean island of St. Kitts. The available information about these infrastructure systems is highly limited, thus, the objective of this paper is to develop a representative model for these systems despite significant data

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limitations. It should be mentioned that the issue of limited data availability might be present for data-rich areas too. Although the requisite data to develop models exist it can be unavailable due to confidentiality reasons. This adds an additional motivation for this paper.

This paper is organized as follows: In the next section (Section 2), background information about St. Kitts and its power and water distribution systems are given along with a description of the threat that hurricanes pose to the island. Section 3 contains a description of the simulation model developed for this case study. In order to demonstrate how this model can be used and what types of modeling results that can be obtained, Section 4 presents the results of analyses aimed at identifying critical components in the systems. Section 5 shows how the model can be used to simulate failures of recent or forecasted hurricanes. Section 6 includes a discussion of the results as well as of the challenges associated with modeling real-world infrastructure systems and the differences between modeling real-world systems and fictional systems. Finally, Section 7 presents the conclusions.

2. Background for the case study

St. Kitts is one of the twin islands of the Federation of St. Kitts and Nevis, which is located in the eastern Caribbean Sea. The nation has an estimated population of about 56,000, with most of the population living on the island of St. Kitts [31]. St. Kitts is a small and elongated island with an area of 69 square miles [30]. The island is of volcanic origin and has a group of volcanic peaks in the middle of the island. Due to these steep mountains, the majority of the population reside by the coastline around the island. The highest populated area is in and around the capital of Basseterre, which is located in the south of the island between the mountains and a peninsula (see the map in Fig. 1).

The power system is operated by St. Kitts Electricity Company Limited (SKELEC), who provide power from 10 diesel generators located at the power station near Basseterre. The power is distributed to the community through 12 lines (11 kV), of which nine are located in and around Basseterre. The remaining three lines stretch along the entire coastline around the island, where one goes along the peninsula to the southernmost point of the island and the other two go up to the north following opposite sides of the island (see the schematic of the main trunk lines in Fig. 2).

St. Kitts is self-sufficient for fresh water. The water distribution system has a production capacity of up to 7 million gallons per day (MGD), which meets the average demand of 5.5 MGD. The different types of water sources come in the form of 30 groundwater wells, 30 surface storage tanks, and 6 river reservoirs. Thus, there is a mixture of groundwater and surface water sources with, on average, 67% of water provided from groundwater sources and 33% from surface water sources. The system is mainly gravity fed. The exception is the wells that require electricity to pump water into the distribution system. A visit to the site found that there were no back-up generators at the groundwater wells. Thus, the water distribution system is dependent on the power system for water production (see the schematic of the modeled water

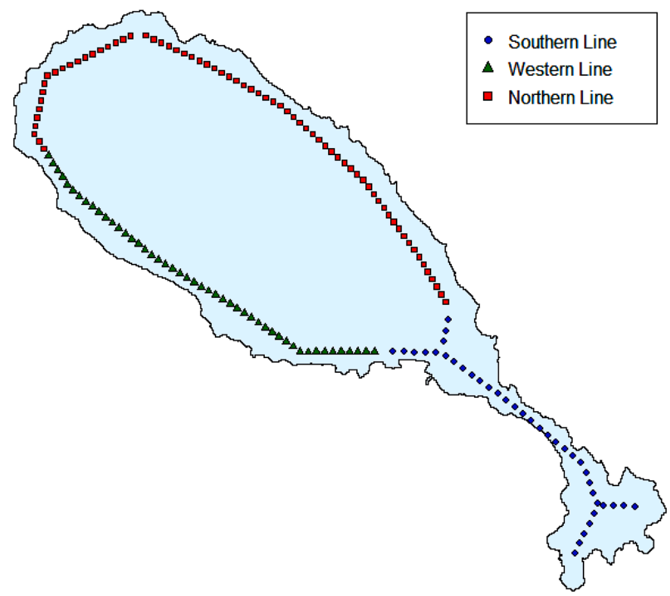


Fig. 2. Schematic of the modeled power system.

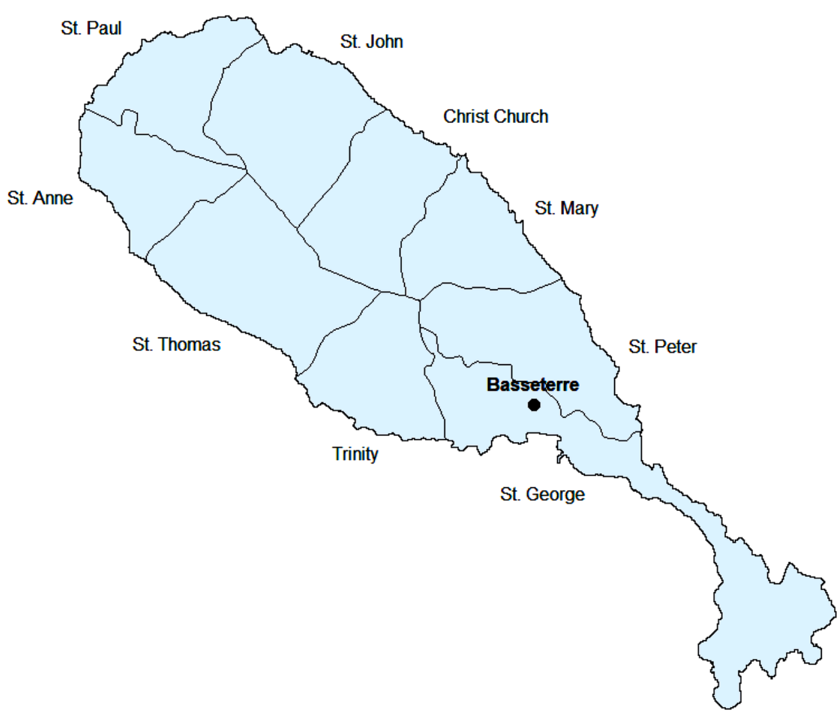


Fig. 1. Map of St. Kitts with parish labels.

system in Fig. 3).

Due to the location of St. Kitts, hurricanes pose a significant threat to the functionality of the island's critical infrastructure. The power system is particularly vulnerable to hurricanes due to its wooden power poles that can fail during strong winds. In addition, the power system in St. Kitts is radial, at least at the time of this case study. That is, there is no redundancy between the lines, particularly between the three lines that provide power to most of the island, discussed further below. When a power outage occurs in an area, the water wells in this area lose their power supply and stop functioning, which puts the water distribution system at risk of negative pressures and insufficient delivery of water. Therefore, in this case study, hurricanes are simulated and used as a natural cause of disruption to the power and water distribution systems. St. Kitts has experienced many strong hurricanes that have caused disruptions to infrastructure systems. Most notably was Hurricane Georges that made landfall on the island in 1998, resulting in severe damage to the infrastructure across all parts of the island. Over 80 percent of all homes were damaged, with some completely destroyed. Severe damages were also seen to other buildings, including the airport, the seaport, the main hospital, schools, businesses, hotels, and emergency shelters. Hurricane Georges resulted in five fatalities and left many people without homes and work, with repair costs reaching approximately $445 million USD [5,14].

3. The simulation model

This section describes how the infrastructure systems and the hurricanes are modeled and how the overall simulation process is performed. This process includes a description of how the power and water system models are coupled together.

3.1. The modeled power system

Very limited information is available about the power system of St. Kitts. The data we do have is from the SKELEC (St. Kitts Electric Company Limited) website [27] and from a visit by one of the authors to the island. Based on this information, the system is modeled as consisting of three main power lines with their center located at the generators near Basseterre. Fig. 2 presents a schematic of the modeled power system. Each line mimics one of the three main trunk lines that surrounds the entire island. In the remainder of this paper, these modeled lines are referred to as the Southern, Western, and Northern power lines. The

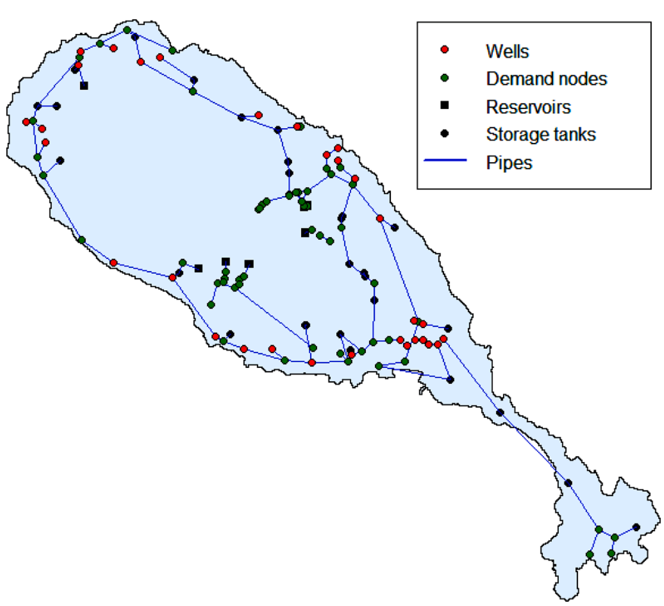


Fig. 3. Schematic of the modeled water system.

Southern power line (represented by dots in Fig. 2) supplies Basseterre as well as the peninsula, the Western power line (triangles) supplies the western coast up to the parish of St. Anne, and the Northern power line (squares) supplies the eastern and northern coast to the point where the Western power line stops. Due to limited information about the power network, the nine smaller trunk lines that are located in and around Basseterre are not included. The exclusion of these trunk lines makes the modeled power system in the Basseterre area a very simplified version of the real system. This causes all the wells in Basseterre to be connected to the Southern power line in the model, instead of potentially being connected to different smaller trunk lines. Without access to more detailed power system data as well as data of exact locations of connection between water wells and the power system, it is difficult to evaluate the severity of this simplification.

A network-based approach is used to model the power system, where the power poles are modeled as nodes and the power lines as the links between the nodes. There are a total of 157 poles in the modeled system, with pole spacing selected to give span lengths (between pole distances) typical of lower-voltage power systems. The ability of the system to provide power at each pole location depends on the status of all preceding poles. If one pole fails due to wind along any of the three lines, all the downstream nodes switch to non-active status and are unable to provide power. That is, there is no redundancy in the system. Because of this lack of redundancy, the failure is assumed to be instantaneous. Note that this is an approximation to the actual power flow. LaRocca et al. [18] showed that such a connectivity-based approach is a poor approximate to actual power flow for high voltage transmission systems. However, for purely radial, lower voltage distribution systems such as the one in our case study, the connectivity-based approach is a much better first order approximation.

3.2. The modeled water system

The water distribution system is modeled using the publicly available widely used software package EPANET 2.0 [25]. EPANET models the hydraulics of water flow in pressurized pipe. We used a demand-driven simulation mode (as opposed to pressure-driven) and assumed there were no pipe breaks in the system. EPANET is widely used in infrastructure modeling in both practice and research, and additional details are available in Rossman [25]. Our EPANET model includes the distribution system pipes along with supply sources and demand nodes. A network schematic of the modeled water system is presented in Fig. 3. The network schematic, supply capacities, and demand values have been provided and approximated based on information from the St. Kitts Water Department. The department provided information on 24 of the 30 wells in terms of both their safe yield and their respective elevations. Because water consumption data are not readily available, the total 5.5 MDG average water demand is partitioned per parish based on its population.

Fig. 3 shows the network flow model of the water system as modeled in EPANET. The red dots represent the wells within the water system and are located around the perimeter of the island. The green dots represent the demand nodes within the model. The water wells and demand nodes are collectively referred to as the water nodes within the model. The reservoirs are represented as black squares and mainly located towards the center of the island, which is the mountainous region. The storage tanks are shown as black dots. Using EPANET allows the movement of water within the system as well as the pressures at each node to be modeled during a simulation of a specified duration.

When the system was first fully mapped to replicate the St. Kitts water system based on the limited information available, there were a significant number of nodes that produced low and negative pressures under normal conditions. Low pressures are in this paper defined as pressures below 20 pounds per square inch [psi]. This pressure limit is chosen because a minimum pressure of 20 psi in water distribution systems is used as a standard in several U.S. states based on pressures needed for fire-fighting activities [9]. Some of the water nodes generate negative pressures that are very close to zero. Therefore, a classification "rule" is made in this study saying that negative pressures are pressures below -1 psi. EPANET was unable to handle the water demand magnitude of each parish effectively, likely because these large demands for each parish are placed at only a few nodes instead of spreading the demand out to replicate the true housing community. The details of these connections to the system were not available, and even in the U.S., demand aggregation to a smaller number of representative nodes is common in developing an approximate hydraulic model for a city. One of the wells in the parish of St. Anne is divided into two wells in the model in order to keep the pressure within the parish from reaching below 0 psi. In order to further mitigate this limitation driven by the available data, the magnitudes of the demands and inflows of water are reduced but kept at the same ratio in order to accurately replicate the overall functionality of the distribution system.

3.3. The hurricane model

Because hurricanes are one of the more frequent causes of disruption to the power and water systems of St. Kitts, we focused on hurricane-induced damage to the power and water systems. Because of the topography of the island and where the population is located, most of the power and water system components that could be sensitive to flooding are either on poles or are at elevations higher than those impacted by coastal flooding. We consequently focus on only wind-induced damage. To estimate wind speeds, we use a parametric wind field model, the same model used in previous work (e.g., [12] and [11]). This model estimates gust wind speed at the location of each well by assuming a parametric decrease in wind speed with distance from the center of the storm. The hurricane track and intensity (central pressure) are input, and the storm is then translated along the track and rotated on its axis to produce the wind speed estimates. The model has been validated against actual time-varying wind speeds in the Gulf Coast region by comparing the wind field estimates with the actual wind fields for hurricanes making landfall in the Gulf Coast region in previous research (e.g., [12]) and has been widely used. Additional details are available in Han et al. [12]. An open source version of the model is available for the R statistical language [4].

This model estimates the maximum wind speed during a hurricane at predefined locations on the island. St. Kitts is divided into nine parishes, each of which is represented by one location in the wind field model. The only exception is for the southernmost parish of St. George which is given three locations because it encompasses the long peninsula and therefore yields different wind speeds depending on where the track is located. Thus, in total 11 locations at St. Kitts are used in the wind field model. The model does not take into account the elevation of the mountainous landscape of St. Kitts. This is likely not particularly limiting for this case study as the power lines are located on the outskirts of the island, which is only slightly above sea level. There may be some reduction in wind speeds on the side of the island sheltered behind the hills in the middle of the island for hurricanes that are close to the island. However, the computational complexity of including these terrain effects would be substantial, and the effects are generally not that large given the small size of the island relative to the size of a strong hurricane.

Based on the resulting maximum wind speeds, the probability of damage to the power poles is computed from the fragility curve presented in Fig. 4. As the maximum wind speeds are simulated on a parish level, also the resulting power pole failure probabilities are given on a parish level. For the case study, this means that all power poles within each parish are given the same probability of failure during a hurricane. The fragility curve was developed through expert judgement (co-author Guikema) based on (1) damage reports of the impacts of previous hurricanes in St. Kitts, (2) previous research on fragility functions for hurricane-induced failures (e.g., [13]), (3) and informal observations of

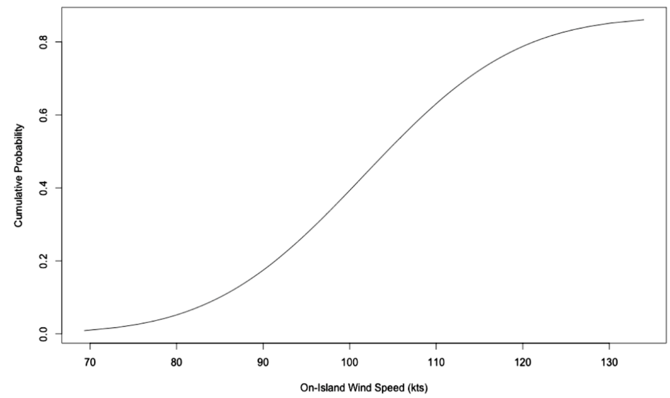


Fig. 4. Estimated fragility curve of the power poles in the St. Kitts power system.

pole conditions during a visit to the island. The damage reports for the Hurricanes Lenny[1], Earl[2], Georges [14], Jose[3], Hugo[4], and Luis[5] are publicly available. However, the reports are not consistent in the information related to damages caused. Some only give information relaying which main island structures were damaged, while others provided specific damage percentages pertaining to the island's power system. The maximum wind speed of Hurricane Georges is used to determine the on-island wind speed that caused the failure of approximately 50% of the poles on the island. The distribution of the fragility curve is based off the reports for Hurricanes Luis, Hugo, Lenny, and Jose using the framework presented by Shafieezadeh et al. [26]. This resulted in a fragility curve with the 50% failure probability associated with 117 miles per hour [mph] or 102 knots [kts] on-island wind speed.

3.4. System dependencies

Since the wells within the water network rely on the input of electricity from the power network to function, the dependencies in the model are formed between all 30 wells within the water network and the power node which they are closest to, allowing multiple wells to depend on the same power node. The electricity within the power network is generated by diesel generators [27] and thus does not rely on input from the water network. Fig. 5 shows the position of the wells in relation to the power nodes and which power nodes each well depends on. The networks within the island are self-contained, and are fairly small in terms of size, making the network relatively simple to model. This allows the electric power and water system of St. Kitts to make a good case study of a real-world dependent infrastructure system.

3.5. The simulation procedure

The process of simulating hurricanes and their corresponding damages to the power and water systems of St. Kitts is a two-stage process. In the first stage, the hurricane of interest is simulated through the hurricane model. As mentioned above, the hurricane model first simulates the maximum on-land wind speeds for each parish before it computes the

[1] https://reliefweb.int/report/anguilla/hurricane-lenny-ocha-situation-report-no-7.

[2] https://reliefweb.int/report/antigua-and-barbuda/cdema-situation-report-3-hurricane-earl.

[3] https://reliefweb.int/report/anguilla/hurricane-jose-post-impact-situation-report-2.

[4] https://reliefweb.int/report/anguilla/hurricane-jose-post-impact-situation-report-2.

[5] https://reliefweb.int/report/antigua-and-barbuda/caribbean-hurricane-luis-sep-1995-un-dha-situation-reports-1-10.

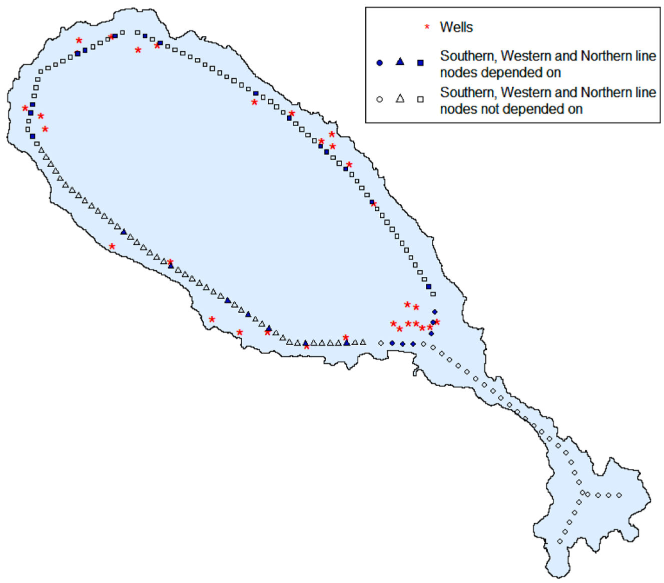


Fig. 5. Schematic illustrating the dependencies within the model.

corresponding failure probability of the power poles.

In the second stage, a Monte-Carlo simulation model is used to couple the power and water system models. First, the power system model simulates which power nodes break based on the power pole failure probabilities. This is done by first assigning each power pole a random value between 0 and 1. The random value is then compared to the respective node's probability of power pole failure. If a node's failure probability is higher than the randomly generated value, the node is set to be failed. This process generates a set of power node failures. We then use a connectivity-based model for the power system. That is, a given node in the system functions (provides power) if (1) there is a path from that node to the generator for which there are no failed nodes and (2) that node itself has not failed. Thus, the power system failure state is generated by setting all power nodes downstream of the initially broken nodes to non-functional.

Next, the state of the water system is computed based on the power system failure state. The power and water distribution systems are coupled through the water wells' dependency on the power system. This dependency is modeled by linking each water well to the power node closest to it, which means that if a power node linked to a well is set to be non-functional, then the well also becomes non-functional. The well states are updated based on the state of the power system, and then the water system is modeled through EPANET for a chosen simulation period (length of time simulated). The simulation period represents the duration of the power outage. This duration can be chosen either based on actual reported power outage durations or estimated based on a best guess of the time it will take the repair crews to arrive at the location, replace damaged equipment, and restore the power. During the simulation, EPANET records the minimum pressures obtained for every node in the water system. This process is repeated for a chosen number of iterations, N, which in this case study is set to 6,000 based on a convergence analysis focused on convergence of the mean. A graphic illustration of the entire simulation process is presented in Fig. 6.

A limitation of this modeling approach is that the functionality states of the nodes in the power and water systems are constant during the simulations in EPANET. This means that if a power outage is simulated to last for 24 hours, the model does not allow for any of the power nodes to be repaired and added back as a functional node during the simulations. In other words, all non-functional power and water nodes remain non-functional throughout the simulation. This could be changed if information were available on pole-level restoration times. However, this was not available for past storms for St. Kitts.

4. Analysis and results

We demonstrate the usefulness of a model such as this by performing two different analyses. The first analysis is a vulnerability assessment that aims to identify critical components in the power system. The second analysis focuses on the linkages between the power and water systems, focusing particularly on how to identify critical wells that would be good candidates for the installation of back-up power.

4.1. Identifying critical components in the power system

To identify the most critical components of the power system in terms of the cascading effects to the water system, simulations of individual power pole failures are performed. In the simulations, one power node at a time is set to fail, causing all down-stream power nodes to stop functioning. The resulting disruption on the water system is estimated for power outage durations of both 12 and 24 hours. Although failures to the power system can be repaired relatively quickly during normal conditions, the restoration time during hurricanes can be much longer due to weather conditions and difficulties for the repair crew of getting to the damage locations. By analyzing two different outage durations (12 hours vs. 24 hours), we can study the effect on the water system of different power restoration times. The simulated disruptions are measured in the form of the average number of water nodes generating negative (< 0 psi), low (0-20 psi) and high (> 20 psi) pressures during the simulation over all 6,000 iterations.

The result of the 24-hour simulations is presented in Fig. 7, where the color of each of the power nodes represents the percentage of water nodes experiencing negative pressure when the given power node is the one node that initially failed. Recall that when one power node fails, all downstream nodes along the given power line also stops functioning. The percentage of water nodes experiencing negative pressures is given by a color scale ranging from white to red, where white means that no water nodes obtained negative pressure and red means that 3.2% of the water nodes obtained negative pressures. The greatest disruption to the water system of 3.2% is obtained when any of the first four nodes along

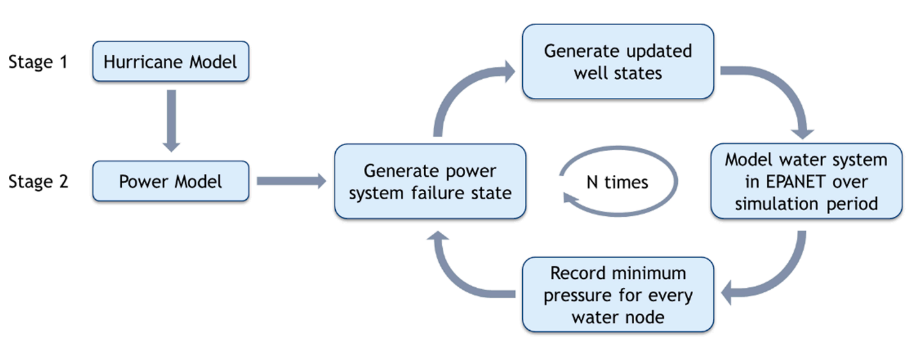


Fig. 6. Graphic illustration of the simulation process.

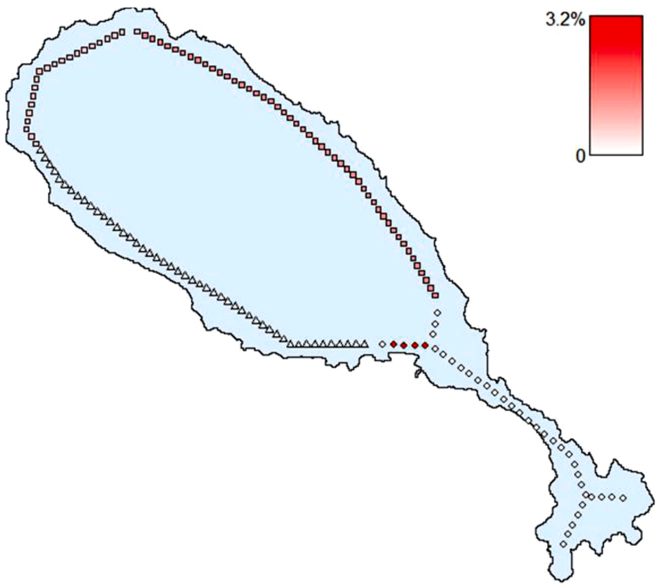


Fig. 7. The percentage of all water nodes having negative pressure during a 24-hour simulation for each single-pole failure simulation. That is, the color of each power node gives the average percentage of water nodes with negative pressures if that power node fails by itself.

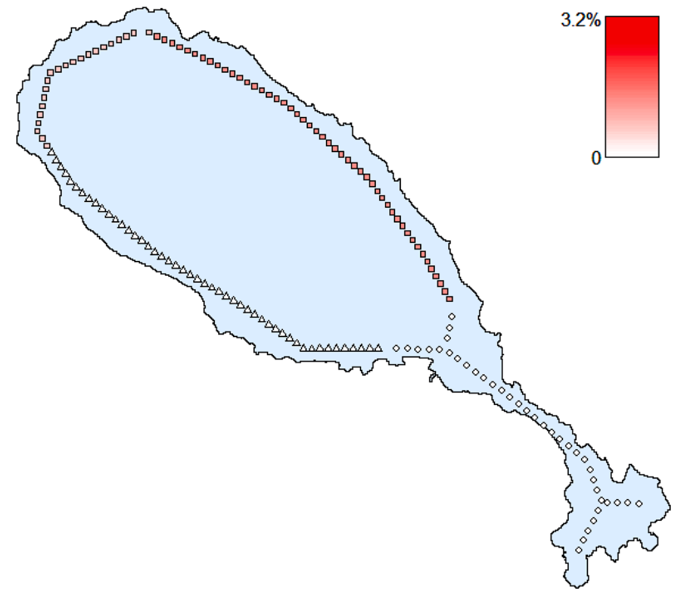


Fig. 8. The percentage of water nodes obtaining negative pressure during a 12-hour simulation.

the Southern power line initially failed. When one of these nodes breaks and all downstream nodes fail, several of the water wells in the capital of Basseterre become non-functional. Basseterre and the surrounding area have the highest water demand on the island. Thus, when the wells in this area stop pumping water into the distribution system over a time period of 24 hours, the water system is unable to maintain a sufficiently high pressure throughout this period.

Negative pressures also appeared when failing any of the nodes along the Northern line. Even failing the very last node along that line causes disruptions to the water system. The reason for this is that this node provides electricity to the well with the highest water production capacity in the water system. This well has a capacity that is almost three times as high as the average capacity across all the wells. As this well is connected to the last power node along the Northern line, the well is affected by power outage when any of the power nodes along the line breaks. In addition to this well, the Northern line also supplies 15 other wells, which correspond to half of the wells in the water system. Thus, failures to this power line cause a reduction in the inflow of water to the distribution system that the water system is unable to cope with over a period of 24 hours. In comparison, no disruptions to the water system are seen by disrupting any of the nodes along the Western line, not even the first node that causes the entire line to fail. These results indicate that the power nodes along the Northern line as well as some of the central nodes in Basseterre are the most vulnerable components of the system.

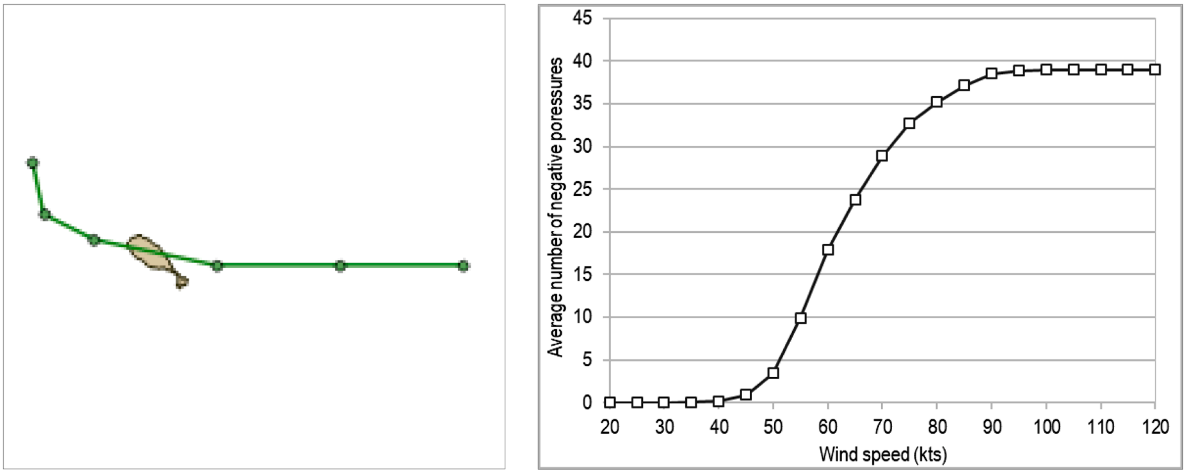
Fig. 8 presents the results when the simulation duration is reduced to 12 hours. In this figure, we observe that single-node failures have the same effect on the water system as during the 24-hour simulations for most of the power nodes. The only exception is for the four power nodes in Basseterre that induced the greatest disruption to the water system during the 24-hour simulations. Failing any of these nodes do not cause any disruption to the water system during a 12-hour simulation. These results indicate that the water system is able to cope without the contribution from most of the wells supplied by the Southern line for a short period of time due to within-system storage, but not for a longer time. Breaking any of the nodes along the Northern power line, on the other hand, caused negative pressures to occur in the water system also for this shorter simulation duration.

4.2. Analyzing linkages between the power and water systems

To identify the critical linkages between the power and water systems, simulations are performed where the wells' dependencies to the power system are removed one well at the time. In real life, this can be done by, for instance, installing a back-up power generator at the site of a well, which will allow the well to function even though there is a power outage in the area. The hurricane used in this analysis is a hurricane that is constructed to make landfall on the island. The hurricane is constructed to move according to typical Caribbean hurricanes that move westwards before bending toward the north. Fig. 9a presents a map of the hurricane track. Different wind speeds ranging from 20 to 120 knots are simulated and the resulting power outage is set to last for 72 hours. Under normal conditions, this is a relatively long restoration time for the power system. However, in the scenario of a hurricane making landfall on the island, it is not unreasonable to assume that it would take at least 72 hours to get the power system back to normal operation. In Fig. 9b, the resulting average number of negative water node pressures obtained over the 6,000 iterations are plotted against the simulated wind speeds. At wind speeds of 100 knots or higher, the hurricane caused the entire power system to fail, which means that none of the wells are functioning. This situation is referred to as the worst-case scenario for the remainder of this paper. In Fig. 9b, we observe that the average number of negative pressures reaches a plateau at 39 (out of a total of 123 nodes in the system) when the hurricane causes this worst-case scenario.

Fig. 10 presents the minimum pressures obtained at each water node when simulating the worst-case scenario in EPANET over a time period of 72 hours, where dark red points represent nodes experiencing negative pressure, light red points represent low pressure (0-20 psi), and white points represent pressures above 20 psi. We can see that negative pressures are appearing throughout the entire distribution system.

The results of the simulations where one well at a time has its dependency on the power system removed are compared to the result of the worst-case scenario. By doing this, we can study how much each of the wells is able to improve the worst-case results. The resulting percentage reductions in the number of negative water node pressures obtained for each of the wells are presented in Fig. 11. The results are given by a color scale ranging from white to green, where white means that there is no reduction in the average number of negative pressures appearing in the water system compared to the worst-case simulation



(a) (b)

Fig. 9. A map of the constructed hurricane track (a) and the resulting average number of water nodes that obtained negative pressure during 72-hour power outage simulations caused the hurricane for winds speeds ranging from 20 to 120 knots (b).

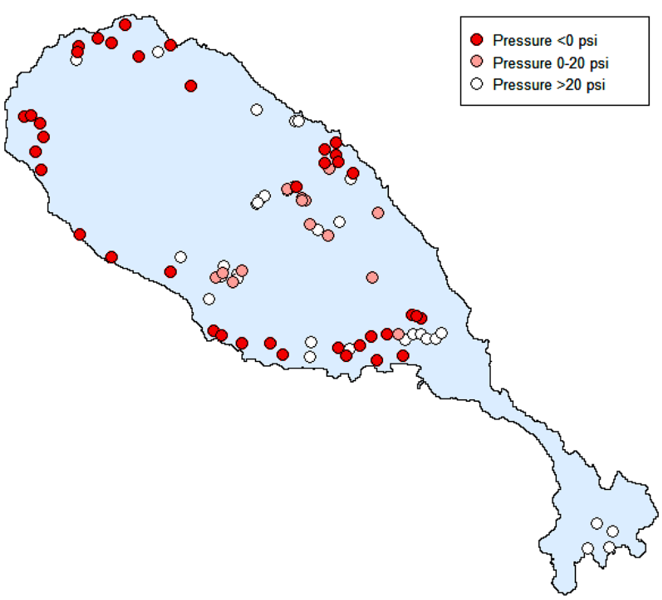


Fig. 10. Minimum water node pressures simulated when no wells are functioning over a period of 72 hours.

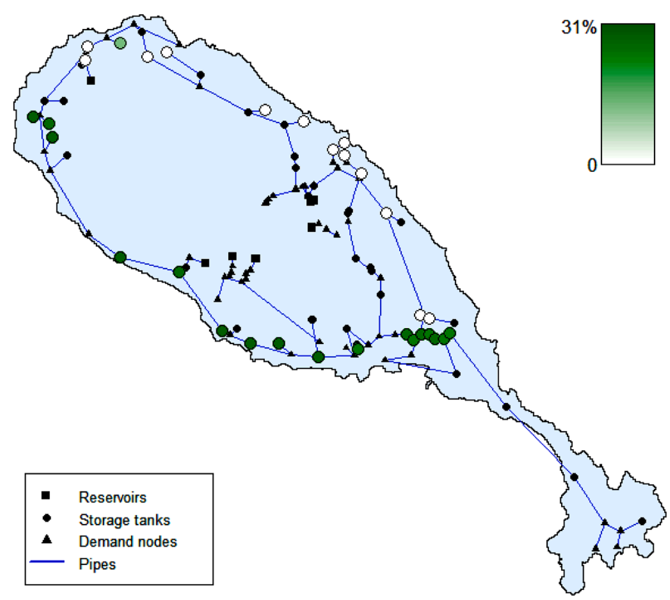


Fig. 11. The percentage reduction in the number of negative water node pressures compared to the worst case where no wells are functioning.

and green means that a reduction of 31% in negative pressures is obtained.

The maximum reduction of negative pressures of 31% is observed when any of the wells along the southwestern coastline has its dependency on the power system removed. In comparison, no wells on the opposite side of the island, except one at the northernmost point of the island, gave any improvements compared to the worst-case simulation. The reason for that northern well showing some improvements is that this well is the second highest water producing well in the system, with a capacity that is 2.5 times as high as the average capacity across all wells. Recall that the well with the highest capacity is one of the three dark green wells located at the westernmost point. Thus, the water production capacity of the wells has some effect on the results. But we can clearly see that the location of the wells seems to have a higher effect, as the wells on the southwestern side of the island show such a high potential of reduced disruptions to the water system while most of the wells on the other side does not show any potential to reduce the disruptions.

An explanation for these results is that the northeastern side of the island has a higher number of reservoirs and storage tanks, i.e., water sources that are unaffected by power outages, than in the southwestern side. In Fig. 11, the reservoirs and storage tanks are illustrated by black squares and dots, respectively. The area in and around Basseterre has the highest water demand. Due to the pressure drop that will be created as a result of the high demand, we believe that the water from both the western and eastern side of the island is flowing towards Basseterre. Since the western side of the island has a fewer number of reservoirs and storage tanks, this part of the distribution system will struggle more to maintain a positive pressure without any contribution from the wells. Thus, the contribution from allowing only one well to function on backup power is higher when this one well is located along the western side of the island compared to on the northeastern side.

5. Model validation

In order to validate the developed model for the power and water system at St. Kitts, a real hurricane is simulated in the model with the aim of comparing the simulated disruptions to the infrastructure systems with the actual disruptions caused by the hurricane. The hurricane used in this validation process is Hurricane Maria, which moved over the Eastern Caribbean Sea in September 2017. When passing St. Kitts on the 19th of September, Hurricane Maria was a category 5 hurricane with its center located approximately 90 miles southwest of the island [2]. Data about the hurricane track and wind speeds are obtained from the National Oceanic and Atmospheric Administration National Centers for Environmental Prediction FTP site [19].

The track and wind speed data obtained for Hurricane Maria is first used as input to Stage 1 of the simulation process (as shown in Fig. 6) to estimate the on-island wind speeds. The on-island wind speed estimates are then used as input to Stage 2 of the simulation process and the probability of power pole damage for each parish is obtained. 6,000 iterations of the simulation are then run to simulate the effects of the hurricane on St. Kitts' power and water systems. For each iteration, a power outage duration of 60 hours is simulated. A press release from SKELEC [28] states that repair crews began assessing the damage of Hurricane Maria on the 20th of September, 2 days after the power system was first affected by the storm. For power restoration after a hurricane, there is typically another 1-2 days to fully mobilize repair resources, especially on an isolated island. Therefore, we estimate that repair work began 60 hours after the power outage began.

The results first focus on the simulated effect of the hurricane on the power system. Fig. 12 shows the frequency over the 6,000 simulations with which each pole is broken due to the hurricane wind. The nodes along the south-western side of the island have the greatest probability of breaking due to Hurricane Maria. This is the side of the island that the hurricane passed closest to and, therefore, experienced stronger wind speeds during the hurricane. It is worth noting that the greatest frequency of pole damage due to the winds within the model is low, at just above 2% at 2.15%.

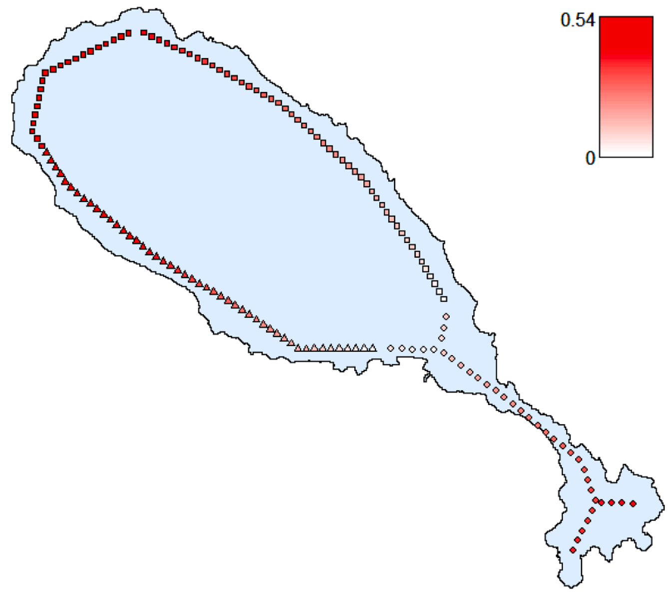


Fig. 13. Frequency of power nodes being in a non-functional state during the simulation of Hurricane Maria.

For each iteration, the cascading effects of the pole damage on downstream power nodes are recorded, allowing analysis of the frequency of each power node not functioning. Fig. 13 shows the frequency that each power pole is non-functional during the simulation of Hurricane Maria. The nodes towards the end of each power line have the greatest frequency of being non-functional. This is as expected, as when a node in a power line breaks, all downstream nodes are set to be non-functioning, and so the nodes towards the end of each power line have a greater probability of being non-functional than those towards the beginning of the line. The greatest frequency of a node being non-functional is 54% of the iterations.

The effects the simulated power outages have on the water distribution is also investigated. First, the frequency with which each well is without power can be shown. Fig. 14 shows that the wells with the greatest frequency of power disruptions follow the same pattern as the frequency of non-functioning power nodes. The frequency is low for those towards the southeast of the island and increases over towards the north-western area of the island, where the ends of both the Western and Northern power lines are located.

The effects of the loss of power at the wells on the water system can be seen in Fig. 15, which shows the water nodes that experienced negative pressures during the simulation. All water nodes that experience negative pressures during the simulation are located in the northern part of the island, situated towards the end of the Northern and Western power lines. These areas are more likely to experience power

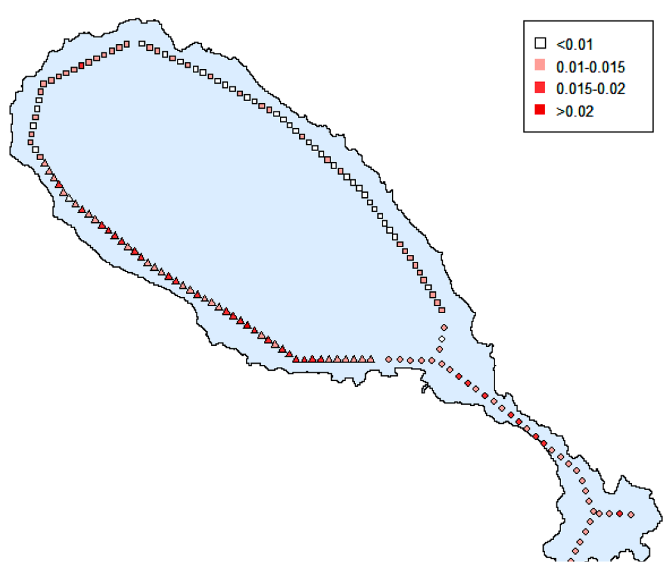


Fig. 12. Frequency of power node breaks during the simulation of Hurricane Maria.

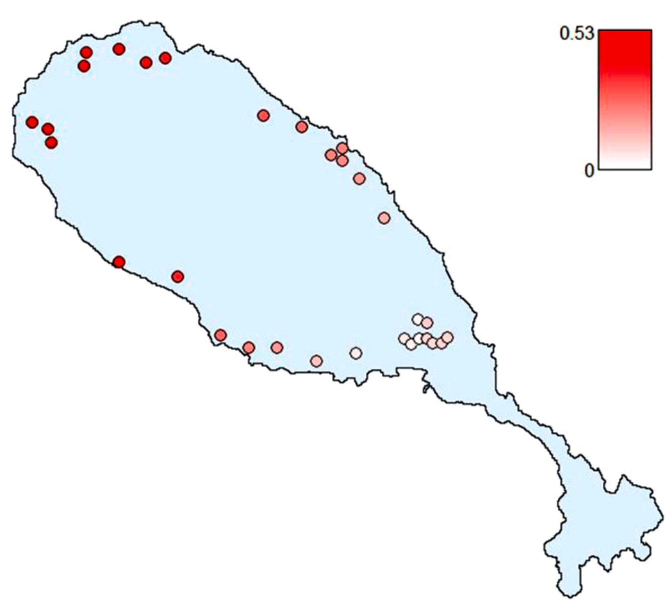


Fig. 14. The frequency of which water wells lost power during the simulation of Hurricane Maria.

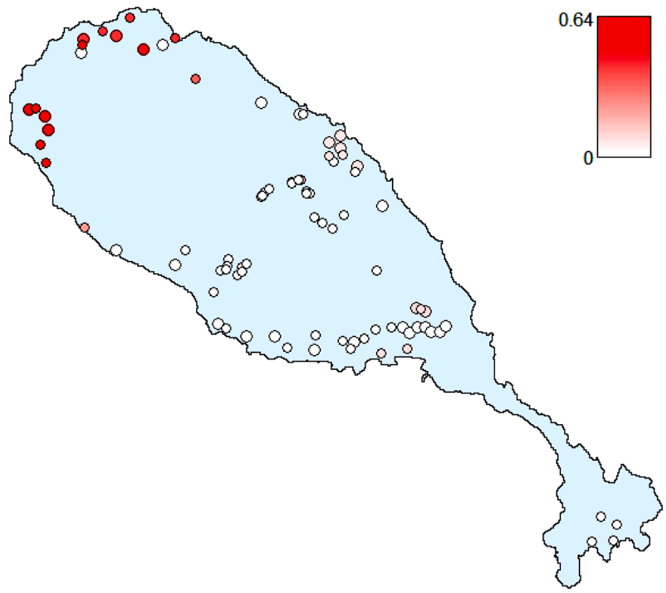


Fig. 15. The frequency of which water nodes experience negative pressures during the simulation of Hurricane Maria.

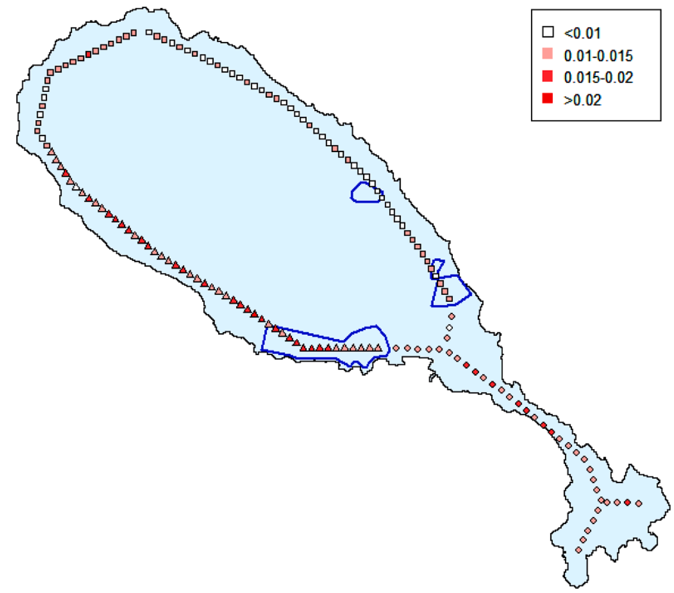


Fig. 16. Comparison of the simulated frequency of power node breaks to the areas of St. Kitts that were reported to lose power due to Hurricane Maria.

outages to the wells, increasing the likelihood that the closer water nodes will experience negative pressures. However, the water nodes in the middle and south of the island are not affected in the simulation.

This analysis can suggest to the water system operator which areas of the system require attention. This could be in the form of introducing redundancy, such as back-up generators for the wells that experience the greatest frequency of power outages during the simulation or in the form of adding storage reservoirs in that portion of the system to increase the ability of the system to withstand short power outages.

The aim of using our model to simulate the effects of Hurricane Maria on the power and water systems is to compare the results to the actual outages that occurred on St. Kitts. Unfortunately, the publicly available information about the actual disruptions to the power and water systems is very limited. This is typical, even in the U.S. The best information about disruptions to the power system is found in a press release at the SKELEC webpage [28], which stated that "Most of our feeders remained intact and online during the passage of the storm. Some like the Canada feeder which services Conaree, Halfmoon and Canada Estates came offline, also Basseterre North Buckley's to Trinity also is fully offline". For the water system, on the other hand, we are unable to find any information about the disruptions caused by Hurricane Maria.

From the limited information found on the effects of Hurricane Maria to the power system of St. Kitts, a crude comparison can be made to the results of our simulations. Fig. 16 shows the areas that SKELEC stated in the press release were offline due to Hurricane Maria and the results of our simulations. As the press release from SKELEC only named areas that were without power, the outline of these areas encompasses the entire residential areas mentioned in the press release and, thus, do not represent the actual outages due to Hurricane Maria.

The areas that were said to be affected in the SKELEC press release are all located close to the start of either the Northern or Western lines, while areas further downstream of all truck lines were not reported to lose power. This suggests that the outages that occurred due to Hurricane Maria were due to disruptions in the smaller distribution lines that are not included in the power model. Comparing the areas affected due to the hurricane with the initial outages seen in the model, the affected area of Basseterre North Buckley's to Trinity (on the south-western side of the island), somewhat matches with power nodes that have a high frequency of breaking during the simulation.

The Canada area of St. Kitts is the smallest area outlined in Fig. 16 (the northernmost outline shown). The press release states that all outages on the eastern side of the island were due to the feeder at Canada being offline. Therefore, the power outages on the eastern side of the island are not due to disruptions to the main trunk lines and thus cannot be compared to the results of our simulations.

No data of the disruption caused to the water system was made publicly available. The only reference to damage within the water system was in the Prime Minister's post Hurricane Maria address stating "Some critical infrastructure such as our electricity and water services… sustained serious damage" [20]. Unfortunately, the lack of information publicly available to the effects of Hurricane Maria on both the power and water systems make validation of the model difficult. However, this is not unusual and points to a research need. We as a research community need to do a better job of collecting and archiving spatially detailed data about the performance of infrastructure systems after natural hazards.

6. Discussion

A model for the dependent power and water systems at St. Kitts has been developed and the area of application for this model has been exemplified by performing two analyses: one that aimed at identifying critical components in the power system and another that analyzed the linkages between the power and water systems. In this section, we will first discuss how results obtained with our model can be used by providing examples of how the results can support decisions regarding system upgrades and emergency preparedness plans. Afterward, we will discuss the challenges faced when modeling real-world dependent infrastructure systems in relatively data-poor environments, as well as the differences between modeling these systems and fictional systems.

6.1. Decision support

Many emerging and developing countries do not have access to the resources needed to quickly repair infrastructure failures, which make them significantly more vulnerable to infrastructure damage and water shortages. The power and water systems on St. Kitts fall into this category. The power and water systems are spread across the entire island, but the operators may not have the resources to immediately fix large-scale blackouts or blackouts located away from the population centers. Therefore, the result of analyses like the ones performed in this paper can be used to support decisions about system upgrades that can help the operators avoid disruptions. The results can also help the operators and society in general to support decisions about emergency preparedness plans. For instance, information about the most critical components of the power system can be used to support decisions about which parts of the power system should be strengthened to better withstand strong winds. Repair crews and spare equipment are scarce resources. Thus, when a hurricane is forecasted and severe disruptions are predicted, the utility operators can benefit from knowing which parts of the system are most critical and therefore which parts of the system should be prioritized to be repaired and where to store back-up equipment required to perform repairs.

The results of comparing the simulated disruptions to the water system during different power outage durations illustrate the importance of getting water wells back in normal operation as fast as possible during downtimes. The results indicate that the water system can cope with power outages in the area of Basseterre for 12 hours, but not for 24 hours. Thus, if the power utility operators are not able to restore the power supply to the water system quickly, the water utility operators should consider other alternatives to avoid loss of service. One possibility is to manually shut down some parts of the system to reduce the pressure drop in the critical areas. Another solution is to supply the critical wells with electricity from a different source such as a back-up power generator. The result of the analysis where the linkages between the power and water systems, i.e., the wells, were analyzed can help support decisions about whether or not to invest in back-up power generators, and if so, where these generators should be installed. The analysis in this paper only simulated the situation where one well at a time had access to a back-up generator. The results indicate that a power generator should be installed to supply any of the wells along the southwestern side of the island. We would like to emphasize that this is not a final recommendation. This analysis is only studying the effect of removing a well's dependency on the power system during a worst-case scenario where the entire island is affected by a power outage. For less severe hurricanes, only parts of the power system will fail, which will cause only a portion of the wells to stop functioning. Such scenarios are not analyzed in this paper. In addition, in this analysis we are only looking at the possibility of removing the dependency between the wells and the power system one well at a time. What if the back-up power generator can supply more than one well at a time? What if two or more back-up power generators can be installed at different locations of the island? These questions cannot be answered from the analysis performed here, and further analysis is required before any conclusions can be made. However, this analysis provides a good example of an area of application for the model.

6.2. Challenges when modeling real infrastructure systems in data-poor areas

From an academic perspective, there are many potential challenges that can arise when modeling real infrastructure systems, especially when dependencies between the systems have to be accounted for. We discuss some of these challenges in this section, focusing specifically on doing this type of modeling in relatively data-poor areas.

The largest challenge is to get access to the requisite data to develop a model. The available data is often limited, which makes the task of developing models that accurately represent the infrastructure systems challenging. The required data includes data about infrastructure topology, i.e., data about how the systems are structured and how they are connected to each other, data about the infrastructure states both during normal operation and during emergencies, and other relevant data that influence operations, like government and corporate policies [24]. The private sector is often the owners of the infrastructures, and thus, the owner of the data. Therefore, regardless of the system being in a data-poor or data-rich area, the data is usually considered sensitive and is therefore kept confidential. Getting access to the data requires approval from stakeholders, which can be hard to achieve [15]. Limited availability of relevant data was a significant challenge for the case study in this paper. As previously mentioned, the only relevant data found about the power system is the publicly available data obtained through the SKELEC webpage. The available data about the water system, on the other hand, is much better as relevant information was provided from the St. Kitts Water Department.

Another problem related to getting access to requisite data is that the available data is not detailed enough or the data might not even exist, which can be the case for operational data. Advances in technology in recent decades have resulted in increased use of sensors and real-time monitoring of infrastructures, which provides large amounts of operational data during both normal operations and crises. However, not all infrastructures utilize these new technologies, particularly in resource-constrained systems. For these infrastructures, the quality of the available operational data is dependent on the routines of documenting abnormalities and accidents during operations. However, even if infrastructure do have up-to-date technology and are capable of recording data related to operations, the issue of the sensitivity of the data again comes into play. Many companies do not want to advertise how much their operations have been impacted when hazards occur. Another worry for companies is how the release of outage data may affect their customers' perception of their ability to operate and their public reputation.

Even if an infrastructure company agrees to share information about their system to be used to develop a model, the data needs to be reviewed regularly to assess how relevant it is compared to the infrastructure. Infrastructures are not static, but instead are constantly being updated either to be better prepared for disruptions or sometimes rebuilt after a disruption occurs. To ensure that the model is representative of the current system, the model developers need information about such updates from the infrastructure management. When modeling dependencies between infrastructures, the dependencies can also change over time and must be considered when assessing if the model is representative of the current systems and their dependencies.

Once the relevant data is available to develop a model, there are always assumptions made in order to go from a complex real-world system to a simpler representation that can be modeled. The more detail included in the model, the more computational power is needed to produce a viable simulation. There is a trade-off process of including enough information within the model that it relates to the real-world system, and not including too much information that the model is slow to run simulations. For dependent infrastructure models, this again extends to the dependencies modelled between the systems. They must represent accurately the interactions between the systems, but not be so complex that the model is difficult to construct.

For the model presented, due to the size and population of St. Kitts, the water and power systems are relatively small compared to systems seen in other parts of the world. Despite being relatively small systems, assumptions were made in order to be able to develop the models. The Water Department of St. Kitts agreed to share the data they had available to them, which included information on 24 of the 30 wells and the demand at the parish level, rather than household level. This affected the water model developed in EPANET which struggled to handle the magnitude of demand and inflow of each parish effectively. In order to combat this issue, the magnitude of the demand and inflow of water was reduced but kept at the same ratio to allow the model to be an accurate representation of the water distribution within the system.

Unfortunately, very limited information on the power system is publicly available, and thus more assumptions were made when developing the power model than the water model. Only three of the main truck lines were included in the model. The information used to develop the model came from information found on the company website, and observations made by members of the Guikema Research Group on the spacing of the power poles of the 3 trunk lines. The smaller distribution lines could not be included in the model due to lack of available information.

The hurricane model used is a model developed previously [12]. A limitation of the wind field model is that it currently does not take the elevation of St. Kitts into account. The mountainous area in the center of the island will have some effect on the on-island wind speeds which is not accounted for in the model. The simulation also only accounts for damage to the power and water systems due to the strong winds experienced during hurricanes and no other events that can also occur such as flooding due to storm surge.

After developing a model, there can be great challenges involved in validating the model, as was experienced in this case study. When collecting data about a disruptive event and its consequences to the infrastructure systems, the same problems as the one faced when collecting system specific and operational data prior to the model development appears. In our case study, we were unable to find public information that in detail described the damages to the systems caused by Hurricane Maria and the duration of the resulting disruptions. An attempt was made to collect data about damages and disruptions caused by other hurricanes too, but even less data was found then. Without access to more data it is impossible to perform a complete validation of the model.

6.3. Why study real systems rather than just fictitious systems?

There have been many studies of infrastructure that have used fictitious systems to study interdependencies. However, relatively few studies have been conducted with real-world examples (e.g., [15]). The available studies have all been done in wealthy countries with considerably higher capacity for collecting and maintaining data on infrastructure systems than our case study.

Real-world studies are undeniably more challenging to perform for academic researchers. The needed data must be gathered if it is even available, and real-world systems are much more complicated than fictitious systems. Why study real systems? One of the main reasons is to better understand if the findings from studies of fictitious systems still hold if more of the complexities of real-world systems are accounted for. Does leaving out the messy, real-world details fundamentally change the insights? In our study, we see that accounting for the actual engineering performance of the water system reveals key insights into where to strengthen it that likely would not be revealed by a more typical network theoretic based approach that does not account for the distribution of demand and the physics of pipe flow. A second key reason for studying real systems is to demonstrate *how* existing methods can be adapted and used given real-world data and, in many cases, the lack of full data about the systems. This is critical for moving these types of analysis tools from academic studies to real-world use.

7. Conclusions

The dependent power and water systems of St. Kitts have been modeled, providing a real-world example of a dependent infrastructure model. Although the data available to develop the model was suboptimal, a simple representation of the island's power and water systems was created. We have seen that dependencies between infrastructures can cause substantial performance degradations, even in relatively simple systems with limited interactions between them. Thus, dependencies, even in simple systems, need to be taken into consideration. We have also shown how improvements within the water system could be made to reduce the impacts of disruptions within the power system. Even with the challenges associated with developing real-world case studies, we have shown that it is possible in a low-data setting to produce a simple model of a real-world case study in a way that could support risk management decision making.

CRediT authorship contribution statement

Kaia Stødle: Conceptualization, Software, Formal analysis, Investigation, Writing - original draft, Visualization. **Caroline A. Metcalfe:** Conceptualization, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Logan G. Brunner:** Methodology, Software, Formal analysis, Investigation, Writing - review & editing. **Julian N. Saliani:** Methodology, Software, Formal analysis, Investigation, Writing - review & editing. **Roger Flage:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition. **Seth D. Guikema:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ress.2020.107421.

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