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Abstract

Modelling interdependent infrastructure systems is a challenging task, and the available information about the infrastructures is often limited. Although a number of methods for modelling interdependent infrastructures have been developed, only a few detailed case studies of risk analysis of real-world interdependent infrastructure systems have been conducted. The objective of this thesis was to present such a case study, and show that it is possible to model interdependent infrastructures with limited amount of information.

This thesis contributes to and extends the work of an unpublished case study by Brunner et al. (n.d.), where a risk analysis of the power and water distribution systems on the island of St. Kitts is performed in relation to the hurricane threat to the island. In the case study, simulation models are used to perform analyses of the power and water distribution systems, as well as for simulating hurricanes and studying the effect of them on the systems. The water distribution system is dependent on the power system due to wells that require electrical power to pump water into the system. Thus, when hurricanes break power poles and cause power outages on the island, the water distribution system is also affected. The information about the infrastructures and the hurricanes that the models are based upon, were publicly available information.

Brunner et al. (n.d.) performed analyses of the power system to identify the most vulnerable parts of the system by simulating historical hurricanes to analyze how these hurricanes affected the power and water distribution systems. This thesis extended to the work of Brunner et al. (n.d.) by performing a synthetic hurricane analysis, where hurricanes were constructed and simulated in order to see if these could provide additional information beyond what the simulation of the historical hurricanes gave. Also, an individual water node analysis was performed, where the wells were analyzed by removing the dependency on electrical power during the simulations for one well at the time.

The results of the performed analyses in this case study have provided information that is valuable from a risk management perspective. It has been shown that risk analyses where interdependent infrastructures are modelled can be conducted, even when only publicly available information is used. The main findings of the risk analysis were that the most vulnerable part of the power system was the powerline that encompasses the eastern side of the island from the main city of Basseterre in the south to the northernmost part of the island. For power outages lasting for multiple days, also a central part of the power system located in Basseterre was found to be particularly vulnerable. In cases where the entire island is affected by a power outage, the most critical wells were found to be the wells located on the western side of the island. The simulation of historical and synthetic hurricanes identified which hurricanes that have the potential to cause the worst damages. Based on these findings, possible upgrades to the infrastructures were suggested, as well as preventative measures that can be implemented to reduce the damages in case of hurricane activity.

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1 Introduction

1.1 Background

The safety, economy, and health of a nation rest upon a well-functioning system of critical infrastructures. Critical infrastructures are described by the U.S. Department of Homeland Security (2016) as those "assets, systems and networks, whether physical or virtual, so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof". Hence, the disruption in the services of critical infrastructures may cause a significant negative impact for the well-being and security of the citizens in a society. Examples of critical infrastructures include electrical power systems, water distribution systems, telecommunication and information systems, transportation and distribution networks, oil and gas production, public health networks, security services, banking and finance and so on (Rinaldi, 2004).

Given the society's reliance on well-functioning infrastructures, a proactive risk management is desirable. The society cannot wait for failures and breakdowns to occur and take lessons from the consequences. Instead, the society must strive to identify vulnerabilities and anticipate possible future problems and threats in order to be able to reduce the risk of failures and breakdowns causing devastating consequences (Johansson and Hassel, 2010). As the systems of critical infrastructures in a society are highly complex, modelling and simulation are important elements of risk analyses. An individual infrastructure alone is complex and challenging to model, but infrastructures do not operate in isolation to one another. They operate together in a complex "system of systems" where the infrastructures are interconnected and interdependent. This means that the function of an infrastructure influences the function of other infrastructures. For instance, the functionality of health and security services requires sophisticated information systems, telecommunication networks require electricity, the generation of electricity requires fuels in many societies, and so on (Rinaldi, 2004). In addition to infrastructures being dependent on each other, there may even be feedback loops causing the failure in one infrastructure system to cascade back to its own system. Dependencies between critical infrastructures and cascading failures are often poorly understood, and even in cases when they are understood, it is very challenging to model the effects of failures of one system on other systems (Johansson and Hassel, 2010). Another challenge of modelling interdependent infrastructure systems is that it is difficult to obtain operational data from the owner of the infrastructures. Therefore, often little information is available about the modelled infrastructures (Rinaldi, 2004).

The research on infrastructure interdependencies is relatively new. Attention to interdependencies between critical infrastructures was given in the mid 1990's due to increased focus on the society's vulnerability to destructions in critical infrastructures because of an increased fear of attacks after the Oklahoma City Bombing in 1995. President Clinton established the President's Commission on Critical Infrastructure (PCCIP) which in 1997 released a report that found no immediate critical threats to the infrastructures in the United States, but it highlighted the dangers of an increasing dependence on critical infrastructures. Since then there has been an increased attention to interdependent critical infrastructures, which has led to funding of researchers working with modelling and simulation of infrastructure interdependencies (Pederson et al., 2006).

A number of methods have been developed for modelling interdependent infrastructures, where examples of such models includes Agent Based models (e.g. the Spot Market Agent Research Tool (SMART) presented by North (2001)), Input-output Inoperability Models (Haimes and Jiang, 2001), and Network theoretic models (e.g. Buldyrev et al. (2010)). Although there has been a lot of research on the modelling of critical infrastructures the last decade, there has been conducted only a few detailed case studies of risk analysis for real-world interdependent infrastructures. Examples includes the modelling of the railway system in southern Sweden that was dependent on a traction power system, a telecommunication system, an auxiliary power system, and an electrical in-feed system by Johansson and Hassel (2010), and the simulation study by Chai et al. (2016) where 16 real medium-voltage power grids which each were dependent on a communication system were analyzed.

Another example is an unpublished case study by Brunner et al. (n.d.), which this thesis builds on. Brunner et al. (n.d.) performed a risk analysis of the power and water distribution systems on the island of St. Kitts in the Caribbean. They used simulation models to study how the water distribution system was directly affected by power outages as a result of hurricane activity. Hurricane simulations were used since tropical storms and natural disasters are the most likely scenario where a powerline would be down for multiple days. 18 different historical hurricanes that all passed relatively close to St. Kitts were simulated. In addition to simulating historical hurricanes, they also simulated scenarios where single power nodes broke and scenarios where parts of the power system broke. This was done in order to identify the most vulnerable points of the power system. Brunner et al. (n.d.) were able to build models that represented the power and water distribution systems of St. Kitts with a limited amount of available data, and thereby showed that risk analyses can be conducted on real-world interconnected infrastructures even in situations with significant data limitations.

1.2 Aim of the thesis

The aim of this thesis was to contribute to and extend the work by Brunner et al. (n.d.). This was done by performing the following analyses:

- Synthetic hurricane analysis.
- Individual water well analysis.

As Brunner et al. (n.d.) only used historical hurricanes when they studied the effect of hurricane activity to the power and water distribution systems on St. Kitts, the contribution from this thesis was to construct synthetic hurricanes and run these through the simulation models to see if that could provide the risk analysis with additional information. The purpose was to identify a potential hurricane that create a worst-case scenario, regarding damages to the power and water distribution system on St. Kitts, or to identify potential hurricanes that not are considered as devastating hurricanes, but that nonetheless could cause surprisingly large damage to the power and water distribution system relative to the wind speed. Therefore, it was of interest to construct synthetic hurricanes with different tracks relative to St. Kitts, i.e. tracks going in different directions and with different distances to the island, and simulate these with varying wind speeds.

The individual water well analysis was performed in order to identify critical linkages between the power and water distribution systems. The linkages between the systems are the wells as they require electrical power to pump water into the distribution system. This analysis was performed by removing the dependency on electric power for one well at the time, and study the improvements in the performance of the water distribution system when a particularly strong hurricane passes St. Kitts.

The objective of performing risk analyses like those in this case study is to identify vulnerable points of the power and water distribution systems. When vulnerabilities are known, upgrades to the power and water distribution system can be planned and executed to make the systems more resistant to external stresses. A secondary objective is to identify potential scenarios where hurricanes cause large damages to the power and water distribution system. By simulating synthetic hurricanes, potential scenarios more damaging than past hurricane experiences might be identified. Being aware of the potential damages hurricane activity can cause to the systems, as well as knowing about the vulnerabilities, the power and water operators on St. Kitts should be able to prepare for better emergency response when stormy weather is reported.

The primary objective of the work by Brunner et al. (n.d.) and this thesis is to present another case study of a risk analysis using a real-world interdependent infrastructure system. A secondary objective is to show that this can be done even in situations with limited amount of data. The hope is that this will help spur more research to improve interdependent infrastructure risk analysis.

1.3 Structure of the thesis

This thesis begins with a presentation of the case study in Chapter 2, which includes relevant information about St. Kitts and the power and water distribution systems. Also, the hurricane threats to the island is described, where an example of a hurricane that have caused large damages in the past is given. In Chapter 3, the simulation models used in this thesis are presented together with details of how the infrastructures in the case study were modelled. In Chapter 4, the previously performed analyses by Brunner et al. (n.d.) are described and presented. Afterwards, the analyses performed in this thesis are described and the results presented in Chapter 5 and Chapter 6, respectively. Chapter 7 discusses the results from all analyses performed both by Brunner et al. (n.d.) and in this thesis. Also, the purpose of performing such a risk analysis as the one in this case study is highlighted by suggesting possible upgrades to the infrastructure and preventative measures that can be implemented to reduce the potential damages to the infrastructures during hurricane activity. Finally, in Chapter 8, a conclusion is given both about whether the objective of performing a risk analysis of real-world interdependent infrastructures with limited amount of data was met, and about the result of the risk analysis.

2 Background for the case study

The case study concerns two real-world interdependent infrastructures; the power system and the water distribution system of the island of St. Kitts in the Caribbean. The water distribution system is directly dependent on the power system because the water distribution system contains ground water wells that utilize electric-powered pumps to pump the water into the system (Brunner et al., n.d.). Failures to the water distribution system can lead to pressure drops in the systems that potentially causes the pipes to collapse.

2.1 General information about St. Kitts

St. Kitts is one of the two islands of the Federation of St. Kitts and Nevis in the eastern Caribbean Sea. The shape is elongated oval with a peninsula that juts out into the sea at the southern end. The island is of volcanic origin and comprises of a group of volcano peaks, where Mount Liamuiga is the highest peak with its 1 156 m above sea level (FAO, 2016). The volcano peaks with their lush scenery are located at the centroid of the main part of the island, and the majority of the population reside where the terrain flattens out near the coastline around the entire island. The economy of St. Kitts was previously based on agriculture, where sugarcane was the main export crop. But as the world prices of sugar went down, the island moved away from an agriculture based to a service based economy. Today, the travel and tourism sector is the main economic activity (FAO, 2016). This economic transition caused a migration of citizen to St. Georges, which today is the highest populated parish with 13,220 citizens out of a total of 34,930 (Brunner et al., n.d.). St. Kitts is divided into nine parishes. A map of St. Kitts with the parish division is presented in Figure 2.1 along with the modelled power lines (green triangles), water nodes, and wells (red and blue dots, respectively). The capital of Basseterre is located within St. George and the southern part of St. Peter. The high population number in and around Basseterre gives the southern parishes the highest demands for electrical power and water. But it should be mentioned that the demands are significant across all parishes. Apart from the capital of Basseterre, the population is generally living in villages ranging in size of a hundred to a few thousand inhabitants (H. Sahely, personal communication, 2014).

2.2 The power system

The power on St. Kitts is generated, transmitted, and distributed by St. Kitts Electricity Company Limited (SKELEC). The power is generated by 10 diesel generators that has a total capacity of 43 MW. The power demand on St. Kitts has a base load of approximately 14 MW and a peak demand of approximately 24 MW (SKELEC, n.d.). The power system comprises a total of 12 powerlines, of which nine are located in and around the most densely populated parishes of St. Georges and St. Peter. The three remaining powerlines surround the entire island. One line goes along the peninsula to the southern part of St. Georges, and the other two go to St. Anne following the coastline on opposite sides of the island (Brunner et al., n.d.).

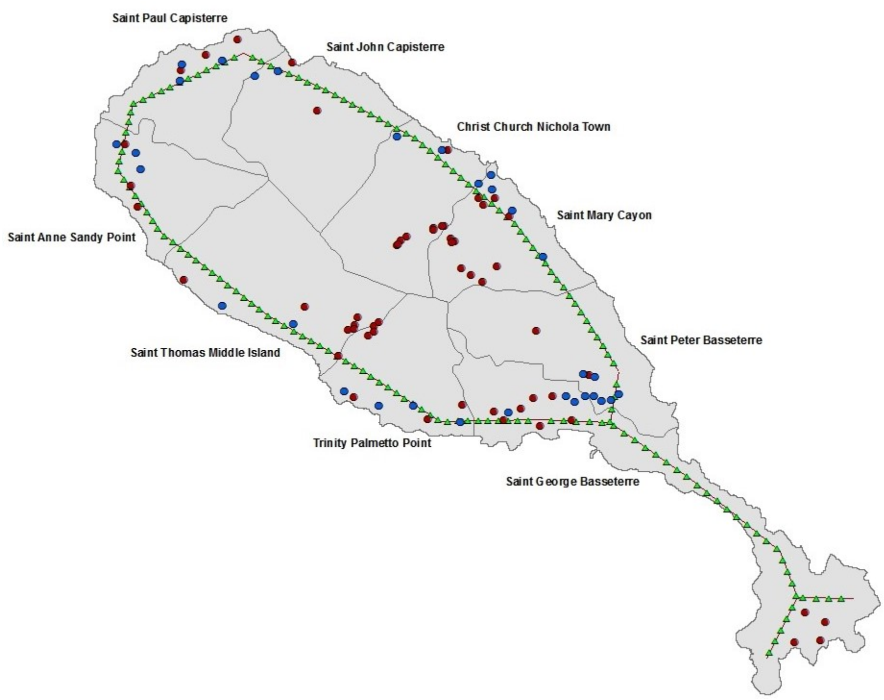


Figure 2.1: *Map of St. Kitts with the modelled power poles shown as green triangles, water nodes as red dots, and water wells as blue dots (Brunner et al., n.d.).*

2.3 The water distribution system

St. Kitts is self-contained with fresh water with a total production capacity of 7 million gallons per day (MDG) and a water demand of about 5.5 MDG. The water is collected from both surface through 6 river reservoirs and groundwater through 30 water wells, where surface water and ground water accounts for about 33 % and 67 % of the production capacity, respectively (Brunner et al., n.d.). The collected water is fed into storage tanks before it is distributed to the public. There is a total of 30 tanks around the entire island which vary in size from 20,000 gallons to 500,000 gallons. The total storage capacity is about 7 million gallons (H. Sahely, personal communication, 2014). Apart from the ground water wells that require electricity to pump water into the distribution system, the system is mainly gravity fed since the communities are built around the volcano peaks.

2.4 Hurricane threats to St. Kitts

St. Kitts is, like all islands of the Caribbean, threatened by seasonal hurricanes. Hurricanes are a huge threat to the critical infrastructures. They can make significant damages to buildings and other properties of the social services like hospitals and health centres, fire and police stations, ports facilities, berthing platforms, and so on. Hurricanes can also cause trees or other objects to fall, which can cause blocked accessibility of roads or damage to power and telecommunication poles and lines. Damages to power and telecommunication systems are common consequences of hurricanes and they can lead to interruption of functions of other infrastructures due to interdependencies. The water distribution system is an example of one such dependent infrastructure. Lost power supply to the pumps in the water wells prevents the water to be fed into the distribution system. As the water distribution system of St. Kitts is partially supplied with water from surface sources and storage tanks and because the system is mainly gravity fed, the system will manage to function for some time during a power outage, but the reduced water supply will over time cause low and possibly negative pressures inside the system that in worst case can result in pipe breaks. Such damages to the water distribution system can be prevented if the operators shut down parts of the distribution system prior to potential power outages. This could extend the life of the distribution system and get water back to the population of St. Kitts quicker (Brunner et al., n.d.).

An example of a hurricane that caused severe damages to St. Kitts is Hurricane Georges that travelled through the Caribbean and Gulf of Mexico in September 1998. Georges passed over the island and left behind five fatalities and destructions worth of approximately $445 million dollars (Hurricane Georges, 1998). The pier and berthing platform of the main seaport in Basseterre was destroyed, phone services were disrupted, and electricity was partially curtailed. Water reservoirs were damaged, and the lack of electricity caused additional damages to the water facilities and hindered the distribution of water. The hurricane caused extensive damages to properties, damaging 60 % of the houses and destroying 25 % of the homes, leaving 2500 people homeless. Schools, commercial business, and public buildings were damaged, including the main hospital. Also, parts of the airport terminal and the control tower were destroyed. The economy of St. Kitts was disrupted through agricultural losses, including a loss of about 50 % of the sugar harvest, and from damages to many hotels, which affected the tourist industry.

3 Description of simulation models

The simulation models that were used in the work of this thesis were made by Brunner et al. (n.d.), and were designed as general simulation models to model power outages and corresponding failures in the water distribution system as a consequence of hurricane activity. The simulation models included a hurricane model programmed in R (R Core Team, 2017), a water distribution system modelled in EPANET 2.0 (Rossman, 2000), and a power outage model programmed in MATLAB (The Mathworks, Inc., n.d.). MATLAB was used as a coupling software that allowed simultaneous simulations of the power and water distribution systems. The different models will be described in more detail in separate sections below. Prior to performing the analyses for this thesis, the provided versions of these models had to be verified by rerunning the simulations performed by Brunner et al. (n.d.) in order to make sure that the models provided the same results as those presented by Brunner et al. (n.d.). This was a comprehensive task as the models were large and each simulation required a long run time. In addition, the generated data sets were large and a considerable amount of time was used to analyze these.

3.1 The hurricane model

The hurricane model was programmed in R, which is a free software environment for statistical computing and graphics (R Core Team, 2017). The hurricane model simulated the maximum resulting wind speeds along used-determined hurricanes tracks through a wind field model by Guikema et al. (2014). Input data for the hurricane tracks were points with track locations and wind speeds. The maximum wind speeds were predicted for predefined tract points, and based on a fragility curve of the power system, the associated probability of failure of the power system for each tract point was found. Instead of only simulating the hurricane tracks with their actual recorded wind speeds, the model was programmed to also simulate each track with 5-knot increment adjusted wind speeds up to 50 knots above and below the actual recorded wind speeds in order to study the effect of different wind speeds on the damage to the power and water distribution systems.

Input data to the hurricane model included data points with track locations and wind speeds of the hurricanes, points of location for each tract centroid, and a fragility curve distribution. Generated output data were maximum wind speeds and corresponding failure probability of the power system for each tract. In the case study of this thesis, 11 tract points were used; one for each of the nine parishes of St. Kitts where St. George was given three points because it encompassed the entire peninsula in the south of the island. The fragility curve used in the case study was created by Brunner et al. (n.d.) by studying publicly available reports describing the damages to main infrastructures on St. Kitts as a result of the following historical hurricanes; Hurricane Lenny (1999), Hurricane Earl (2010), Hurricane Georges (1998), Hurricane Jose (1999), Hurricane Hugo (1990), and Hurricane Luis (1995). The fragility curve presents the cumulative probability of failure in the power system caused by hurricanes exceeding a given wind speed. The resulting fragility curve had a normal distribution with mean and standard deviation of 117 and 16 mph, respectively (see Figure 3.1).

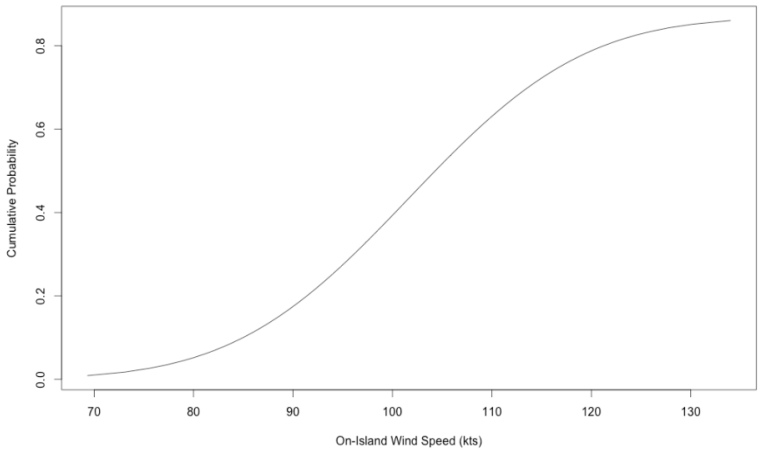


Figure 3.1: *Estimated fragility curve of the power system of St. Kitts (Brunner et al., n.d.).*

The wind field model was limited to not taking elevation of the landscape into account, but that limitation was likely not of importance for the case study since the powerlines at St. Kitts surrounds the island close to sea level and does not pass over the volcano.

3.2 Water distribution system modelling

The water distribution system was modelled in EPANET 2.0, which is a publicly available software that simulates hydraulic and water quality behaviour within pressurized networks (Rossman, 2000). The required input data to EPANET was a network representation of the water distribution system where the demand and supply sources are represented by nodes connected by pipes and valves. In addition, relevant properties like properties of the nodes, pipes, valves, hydraulic, water quality, bulk flow reaction rate, simulation time, and so on was required. By running EPANET, the movement of water inside the system was simulated and the pressure at every node during the simulation period was estimated.

In the case study, the water distribution system at St. Kitts was represented in a network where both the water nodes and the water wells were represented as junction nodes, the reservoir sources as reservoir nodes, and the surface storage tanks as tank nodes (see Figure 3.2). The network would had been too comprehensive if the water nodes were spread out to replicate the true house holding at St. Kitts. Therefore, the demands for each parish was placed at a few nodes. When EPANET was run with the actual magnitudes of the demands and inflows of water, the result was that a significant number of water nodes produced negative or low pressure. Therefore, the magnitudes of the demands and inflows of water were reduced, but kept at the same ratio to accurately replicate the overall continuity of the distribution system. The total water demand of 5.5 MGD was portioned per parish based on its population number because the water consumption data was not readily available (Brunner et al., n.d.).

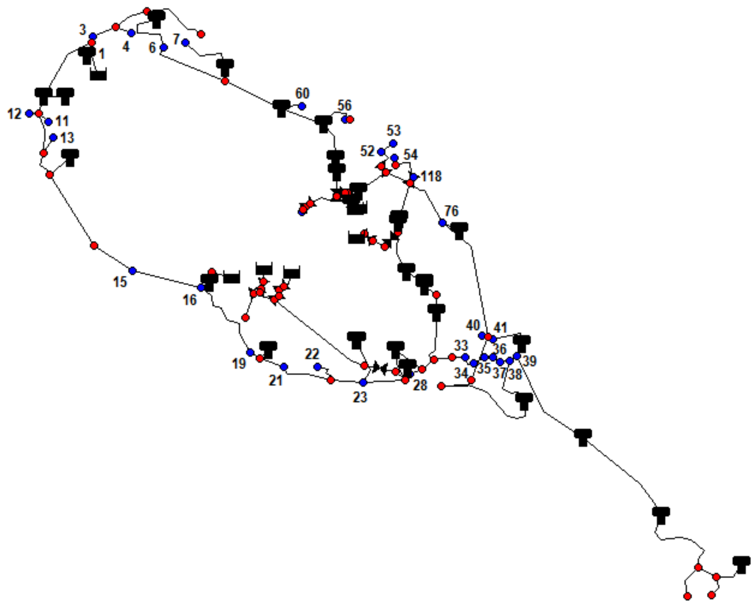


Figure 3.2: *EPANET network representation of the water distribution system at St Kitts, with the water nodes shown as red junctions nodes, water wells as blue junction nodes (with labelled well id's), and reservoir sources and storage tanks as black reservoir nodes and tank nodes, respectively.*

3.3 Power outage modelling

The power outage model was programmed in MATLAB, which is a software environment for numerical computation and visualization (The Mathworks, Inc., n.d.). The power outage model had two menu options that performed different tasks; *Menu option 1: Create lookup table*, and *Menu option 2: Run hurricanes based off of hurricane probabilities.*

3.3.1 Menu option 1: Create lookup table

The task of Menu option 1 was to create a lookup table of water node pressure data that Menu option 2 later utilized when running hurricanes. The code started by breaking combinations of power nodes, from one broken node up to the number of powerlines, which in the case study were three. Details about the modelled powerlines in the case study will be described later. The status of a power node depended on the status of all preceding power nodes. Hence, when a power node broke, all downstream nodes were set to be non-functioning. All possible scenarios of power node failures were identified. In the model, each water well node was connected to its closest power node. Therefore, all combinations of non-functioning water wells were found directly by comparing the scenarios of non-functional power nodes with a list of connected power and water nodes. A *non-functioning water well* meant that the water well pump had no power supply and could not deliver water to the distribution system. For each combination of non-functioning wells, the model called upon EPANET by using the EPANET Programmer's Toolkit (US EPA, 2008), and changed the demand settings of the non-functioning water wells to zero before EPANET simulated the minimum pressure inside the system over a user-determined time period. The generated minimum pressure at each water node was recorded in a lookup table together with information about the non-functioning power nodes and water wells for each scenario. As there were some generated pressures that were negative, but very close to zero, a classification "rule" was made by Brunner et al. (n.d.) that said that a pressure had to be below -1 psi to be considered negative.

3.3.2 Menu option 2: Run hurricanes based off of hurricane probabilities

Menu option 2 randomly chooses which power nodes to break based on the probability of failure of the power system that was generated by the hurricane model. As the hurricane model predicted the failure probability for tracts only, all power nodes within one tract was given the same failure probability. The code started by performing a power node analysis. Each power node was assigned with a randomly generated value from 0 to 1 that was compared to the failure probability. If the random number was below the failure probability, the power node would be broken and all downstream power nodes non-functioning. A binary adjacency matrix showing the functionality of the power nodes was created. Water nodes that were connected to any of the broken power nodes were set as non-functioning. The scenario of non-functioning water wells was looked up in the table of minimum water pressures generated in Menu option 1, and the minimum pressure for every water node was recorded. This process of constructing scenarios of power outages and looking up water nodes pressures for all corresponding scenarios of water well breakages was repeated N number of times. In the case study, the number of iterations, N, was set to 6000. Pressure data for all water nodes was recorded in each iteration and in the end the average number of negative pressures was calculated and the median pressure found. The whole process of Menu option 2 was performed for all simulated hurricane. The process is graphically illustrated in Figure 3.3.

3.3.3 The case study power system

In the case study, the power system was modelled with the three powerlines that surround the island of St. Kitts; the Western line, the Northern line, and the Southern line. The nine powerlines within the St. Georges and St. Peters parishes were not included. All three powerlines

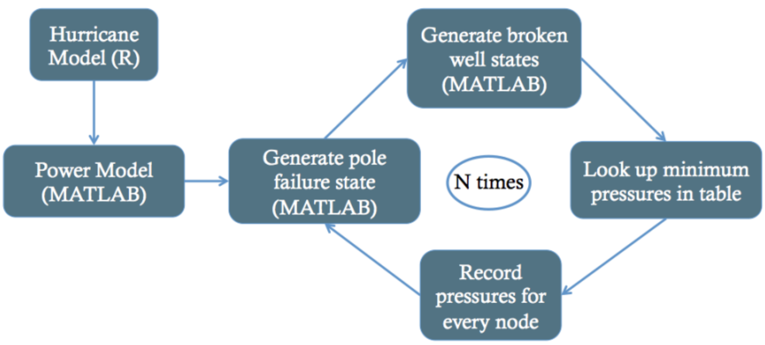


Figure 3.3: *Graphic illustration of the process of Menu option 2: Run hurricanes based off of hurricane probabilities (Brunner et al., n.d.).*

had a starting point in the main city of Basseterre. The Western powerline supplied the western coast, the Northern powerline supplied the eastern and northern coast, and the Southern powerline supplied the southern part of the island including Basseterre. The Western and Southern powerlines were both ending in the St. Anne parish. The power system model consisted of a total of 157 power poles, which each was modelled as a power node in the system (see Figure 2.1 for a map of St. Kitts where the power nodes are illustrated). Table 3.1 presents data about the number of power nodes and parishes spanned for each powerline as well as the number of water wells each of them supply and the total percentage water demand of the area around each line. Among the three powerlines, the Northern powerline is modelled with the largest amount of power nodes, which is natural as the line occupies more parishes. The Northern powerline supply power to the largest number of water wells and has the largest water demand for the same reason. The percentage water demand and number of wells are relatively high for the Southern powerline as well when considering the lower number of power nodes and spanned parishes.

Table 3.1: *Properties of the three modelled powerlines; Western, Northern, and Southern (Brunner et al., n.d.).*

Powerline	**Western**	**Northern**	**Southern**
Percent of Total Water Demand	22.2 %	45.6 %	32.2 %
Number of Wells	7	16	8
Number of Power Nodes	48	70	39
Number of Parishes Spanned	4	6	2

4 Previous analysis results

Brunner et al. (n.d.) performed simulations of individual power node outage scenarios, parish-by-parish outage scenarios, and historical hurricane simulations. The results they obtained from each of the different analyses are presented in this section.

4.1 Individual power node analysis

In the individual power node analysis, each power node that was connected to a water well was analyzed using 12-hour and 24-hour outage simulations. All downstream power nodes of the broken nodes were set to be non-functioning, while all remaining power nodes in the system were functioning. The purpose of this analysis was to determine threshold points for potential damage to the water distribution system of losing power nodes along each powerline. The results from the 24-hour outage simulation showed that power node outages along the Western powerline had little effect on the water distribution system regarding damages to water nodes, while power node outages along both the Northern and Southern powerlines both resulted in negative pressures appearing in the water distribution system. Three threshold points that caused an increase in damage potential along each powerline during the 24-hour simulation were identified; two in the Northern power line, where one was located in the parish of St. Anne and the other in the parish of St. Paul, and one in the Southern powerline in the parish of St. Georges. The threshold points are illustrated as black dots in Figure 4.1. In the figure, a grey dot indicates that breaking that power node results in the same number of negative water node pressures as when the previous black dot was broken, i.e. there was no increase in affected water nodes, while a white dot indicates that breaking that power node had no effect on the water distribution system regarding negative pressures. It can be observed that breaking any one of the power nodes along the Western power line had no effect on the water distribution system, while breaking almost any of the power nodes along the Northern powerline resulted in negative pressures appearing. For the Southern powerline, the failure of four of the power nodes caused negative pressures to appear in the distribution system, and these four were located in the main city of Basseterre.

The threshold points identified in the 12-hour simulations were not the same as those identified in the 24-hour simulations. The reason is that the water distribution system had to function with its natural demand for a shorter period of time. The results obtained by breaking power nodes along the Western and Northern powerlines during the 12-hour simulations were similar as to the results from the 24-hour simulations; power node breaks along the Western powerline resulted in no negative pressures in the distribution system, and power node breaks along the Northern powerline resulted in the same number of negative pressures as for the 24-hour simulations. The results of power node breaks along the Southern powerlines, on the other hand, were not the same in the 12-hour and 24-hour simulations. Unlike the 24-hour simulation, no negative pressures appeared in the southern water nodes during the 12-hour simulations. Not even low pressures, i.e. pressures below 20 psi, were recorded at any of the water nodes. These results indicate that the water input from river sources and storage tanks are able to cope with power outage along the Western and Southern powerlines, provided it is for a short period of time. Despite the short timescale, the Northern powerline had the same number of negative pressures in both the 12-hour and 24-hour simulations, which means that the Northern powerline is more vulnerable to failures.

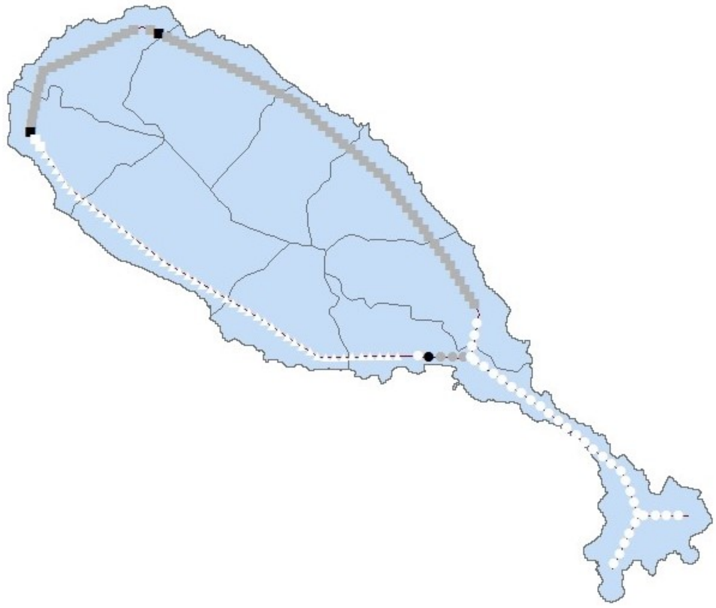


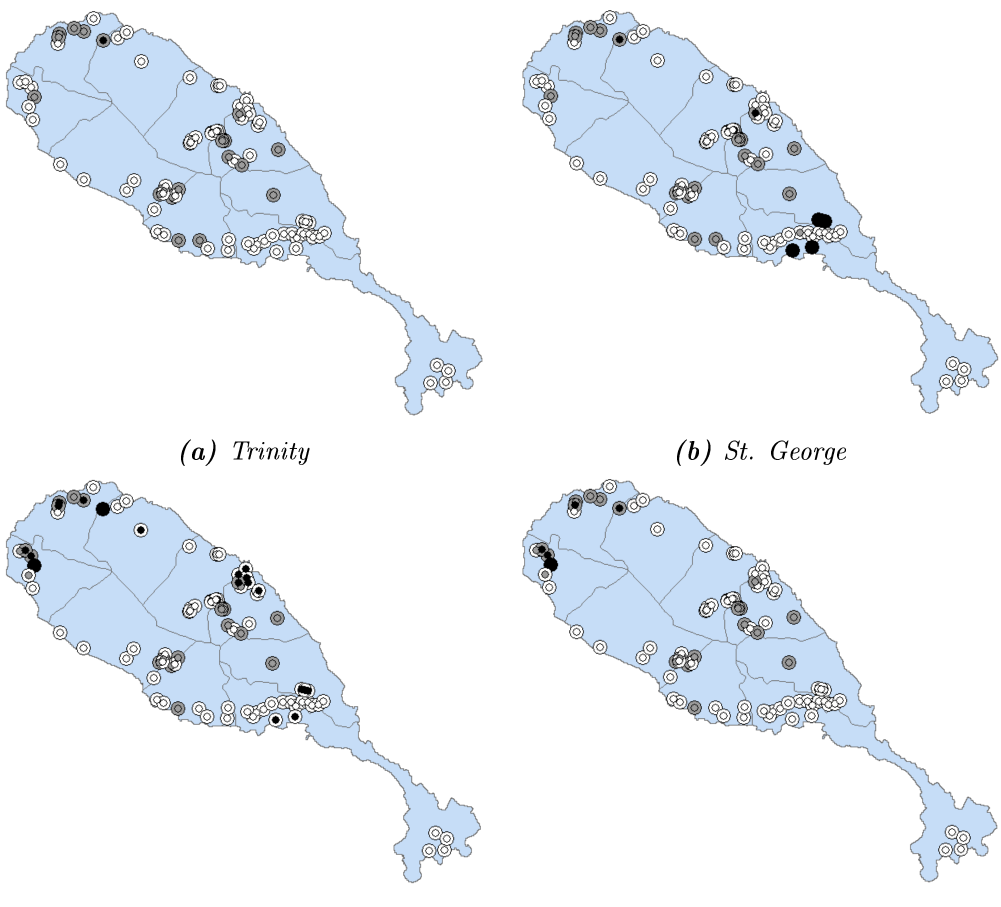
Figure 4.1: *Illustration of the vulnerable power nodes when only a single node is broken at the time for a 24-hour simulation period. The different shapes represent different powerlines; the triangles represent the Western line, the circles represent the Southern line, and the squares represent the Northern powerline. The different colors represent different effect of breaking a power node; black indicates that breaking that specific node caused an increase in the number of broken water wells, grey indicates that breaking that specific node resulted in the same number of broken water nodes as the previous black node, and white indicates that breaking that specific node had no effect on the water distribution system (Brunner et al., n.d.).*

4.2 Parish-by-parish power outage analysis

In the parish-by-parish outage analysis, all power nodes within one parish were broken at the time and each scenario was run for 12, 24, 48 and 72 hours. Simulations of parish-wide outages were done to pinpoint potential threshold points along each powerline as well as to compare which powerlines that caused the worst outcome if only one were to break. The results were then compared to see if the functionality in a certain parish stayed consistent as the duration of the power outage increased or if negative pressures would appear in new wells and new threshold points observed. Figure 4.2 presents the median pressure for each water node from all iterations during the 24-hour and 48-hour simulations for four of the parish-wide outages; Trinity, St. George, St. Peter, and St. Anne. Power outage in the parishes of Trinity, St. George, and St. Peter caused the largest amount of non-functional power nodes along each of the powerlines (Trinity for the Western, St. George for the Southern, and St. Peter for the Northern) since the power had to be transported through these parishes to supply the remaining power nodes in parishes further down the lines. Results from the power outage analysis of the parish of St.

Anne are included because it caused the smallest amount of damage to the Northern powerline since the powerline ends in that parish. The outer circles represent median water node pressure from the 24-hour simulation, while the inner circles represent median water node pressure from the 48-hour simulations. The pressure values are color coded, where white represents pressures >20 psi, grey represents pressures between 0-20 psi, and black represents pressures <0 psi. As mentioned in Section 3.3.1, only pressures below -1 psi were considered as negative pressures in order to exclude pressures that were negative and very close to zero. This rule applies to the results, which means that although the boundary value between grey and black pressure states was defined as 0 psi in the results, the real boundary value was -1 psi.

In the Trinity simulation (Figure 4.2a), which analyzed the worst-case scenario if only the Western powerline were to break, no negative pressures appeared during the 24-hour simulation and only one negative pressure appeared during the 48-hour simulation. In the St. George simulation (Figure 4.2b), which broke both the Southern and Western powerline, negative water node pressures appeared in the area of the capital of Basseterre in both the 24-hour and 48-hour

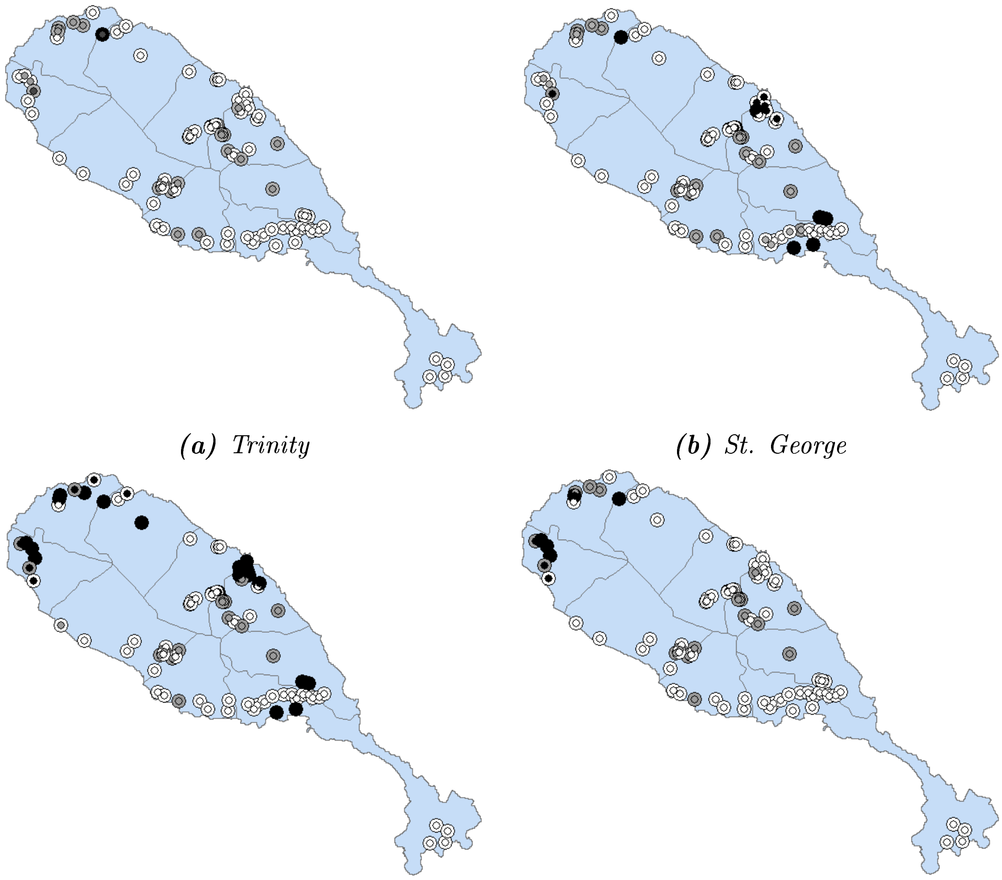


(a) Trinity *(b) St. George* *(c) St. Peter* *(d) St. Anne*

Figure 4.2: *Schematics of the median water node pressures for parish-wide outages of 24-hour and 48-hour simulations, where the outer circle represents the 24-hour pressures and the inner circle represents the 48-hour pressures. The different colors represent different pressure values; white represents pressures >20 psi, grey represents pressures between 0-20 psi, and black represents pressures <0 psi. The results from the following parish-wide outages are presented; (a) Trinity, (b) St. George, (c) St. Peter, and (d) St. Anne (Brunner et al., n.d.).*

simulations. When the 48-hour simulation was compared to the 24-hour simulation, an increase of two negative pressures were observed, and these negative pressures appeared in water nodes along the north-east coast. The highest number of negative pressures was observed in the St. Peter 48-hour simulation (Figure 4.2c), which analyzed the worst-case scenario for the Northern powerline. Negative pressures appeared along the entire Northern powerline and in the area of the capital of Basseterre. In the 24-hour simulation, only two negative pressures appeared which both were in the north. In the St. Anne simulation (Figure 4.2d), which only broke the last part of the Northern powerline, similar results as for the St. Peter simulations were observed when only studying the parishes of St. Anne and St. Paul. No negative pressures appear in the remaining parts of the island.

The results from the 72-hour simulations were similar to those from the 48-hour simulations. Figure 4.3 presents the median pressures from the same parish-wide power outages as Figure 4.2, but for the 48-hour and 72-hour simulations. In the Trinity simulation, only one new negative pressure appeared in the 72-hour simulation compared to the 48-hour simulation (Figure 4.3a). In comparison, six new negative pressures appeared in the St. Peter simulation, of which all



(a) *Trinity* ***(b)*** *St. George*

(c) *St. Peter* ***(d)*** *St. Anne*

Figure 4.3: *Schematics of the median water node pressures for parish-wide outages of 48-hour and 72-hour simulations, where the outer circle represents the 48-hour pressures and the inner circle represents the 72-hour pressures. The different colors represent different pressure values; white represents pressures >20 psi, grey represents pressures between 0-20 psi, and black represents pressures <0 psi. The results from the following parish-wide outages are presented; (a) Trinity, (b) St. George, (c) St. Peter, and (d) St. Anne (Brunner et al., n.d.).*

of them appeared in the north (Figure 4.3c). The highest increased was observed in the St. George simulation where seven new negative pressures appeared (Figure 4.3b), which almost doubled the total number of negative pressure to 15. All the new negative pressures appeared in the parish of St. Mary, which is close to the water input points of two of the river sources. Brunner et al. (n.d.) concluded that this was an example of a threshold point for this part of the system since the water inflow from the rivers ensures that the pressures remain positive at the surrounding water nodes during a 48-hour power outage situation, but not during a 72-hour outage situation.

The results from the parish-by-parish outage analysis confirmed the results from the individual power node analysis as these results also indicated that Western powerline is the least important powerline in terms of vulnerability out of the three powerlines, while the Northern powerline is the most important. Brunner et al. (n.d.) concluded that since the Northern power line supplies parts of the water distribution system that encompasses almost half of St. Kitts' water demand, it is essential that this line stays functional if the focus is to limit damages to the distribution system. The St. Anne simulations showed that although only a small part of the Northern powerline failed, it caused a significant number of negative pressures to appear in the north. Power outages in the north are harder to repair than outages in the south as the power station and the operators are located in the area of the capital of Basseterre.

4.3 Simulation of historical hurricanes

Brunner et al. (n.d.) performed simulations of 18 different historical hurricane tracks. These hurricanes were chosen because all of them had their track relatively close to St. Kitts and they all had available track information on the NOAA track website (NOAA Office for Coastal Management, n.d.). In addition, the hurricanes had varying wind speeds and track directions, which would apply varying stresses to the power and water distribution systems. Figure 4.4 shows the hurricane tracks as they pass St. Kitts, and Table 4.1 presents the wind speed at their closest recorded track point; the distance between their closest recorded track point and the island; the estimated minimum distances between their tracks and the island; and the directions to the tracks relative to the island. The estimated minimum distances between the tracks and the island were estimated by calculating the minimum distance between the island and a constructed straight line between the two closest recorded track points for each hurricane. These estimated distances were not presented by Brunner et al. (n.d.), but calculated during the work of this thesis. They were calculated to give a more realistic picture of the minimum distances between the hurricane tracks and the island. As the closest track point for a hurricane was not necessarily recorded at the time the hurricane was closest to the island, the distances calculated between the closest recorded track points and the island could be very different from the real minimum distance. Among all the 18 hurricanes, only one made landfall on St. Kitts, namely Hurricane Georges, as mentioned in Section 2.4. The estimated minimum distance between Georges and the island is presented as 12 km in Table 4.1 because the center of the storm hit land on the southernmost point of the peninsula which is approximately 12 km away from the point in the center of the island that was used in the distance calculation. The closest hurricanes to St. Kitts after Georges, were Irene, which passed on the south-western side of the island by an estimated margin of about 28 km, and Jose, which passed on the north-eastern side of the island by an estimated margin of about 29 km.

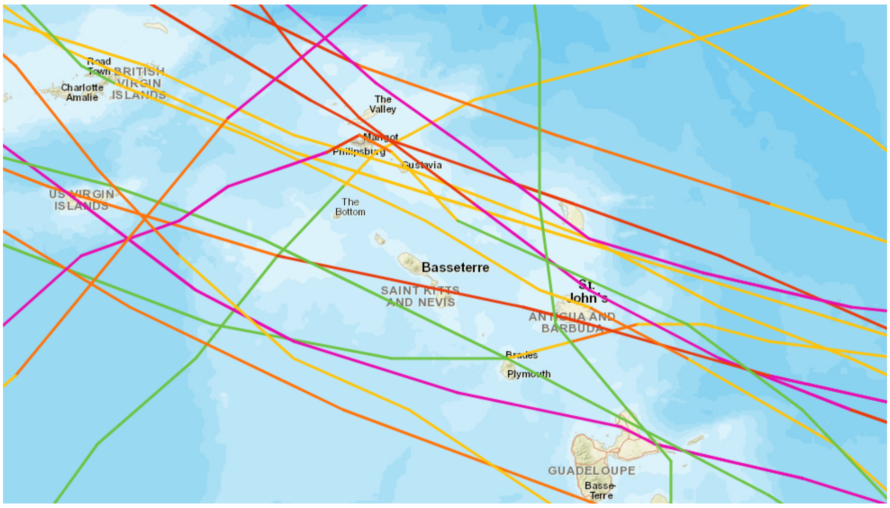


Figure 4.4: *Map of the 18 historical hurricane tracks as they pass St. Kitts (NOAA Office for Coastal Management, n.d.).*

Table 4.1: *Simulated historical hurricane data including; the wind speed at the closest recorded track point, the distance between the closest recorded track point and St. Kitts, the estimated distance between the track and St. Kitts, and the direction to the track relative to St. Kitts, i.e. at which side if island the hurricane passes.*

Hurricane	**Wind speed at closest track point (kts)**	**Distance between the closest track point and the center of St. Kitts (km)**	**Estimated distance between track and the center of St. Kitts (km)**	**Direction to the track relative to St. Kitts**
Alice	70	50	46	NW
Baker	80	70	66	S
Bertha	75	105	46	NE
Betsy	70	104	103	SW
Debby	65	113	54	NE
Dog	105	79	79	NE
Donna	130	91	73	NE
Earl	95	125	109	NE
Erika	75	216	216	NE
Georges	100	88	12	-
Hugo	125	88	71	SW
Irene	45	87	28	SW
Iris	50	106	106	E
Jose	80	29	29	NE
Lenny	60	41	41	NE
Luis	115	83	82	NE
Marilyn	80	94	87	SW
Omar	115	152	148	NW

Simulation results of the historical hurricane simulations are presented in Table 4.2. From the hurricane simulations in R, the maximum on-island three-second wind gust speed and the average probabilities of power node failure are listed, and from the power outage and water distribution modelling, the average number of negative water node pressures during the 72-hour simulations are listed. The hurricanes are ordered from highest to lowest on-island wind gust speed. The fact that Hurricane Georges made landfall on the island together with its high recorded wind speed of 100 knots at the closest track point, resulted in Georges having the highest maximum on-island wind gust speed of 102.4 knots, the highest probability of failure of the power system of 0.429, and the highest average number of negative water node pressures of 35.37. In the bottom of the list, Hurricane Iris, Hurricane Irene, and Hurricane Erika are placed. During the 72-hour simulations of these hurricanes, no negative pressures appeared. Hence, although Irene was the closest hurricane after Georges, no negative pressures appeared. This can be explained by Irene's low wind speed of 45 knots recorded at the closest track point. Also Iris had a low recorded wind speed of 50 knots at its closest track point. The reason for Erika causing little damage is its estimated distance of 216 km from the island, which was the furthest of all hurricanes.

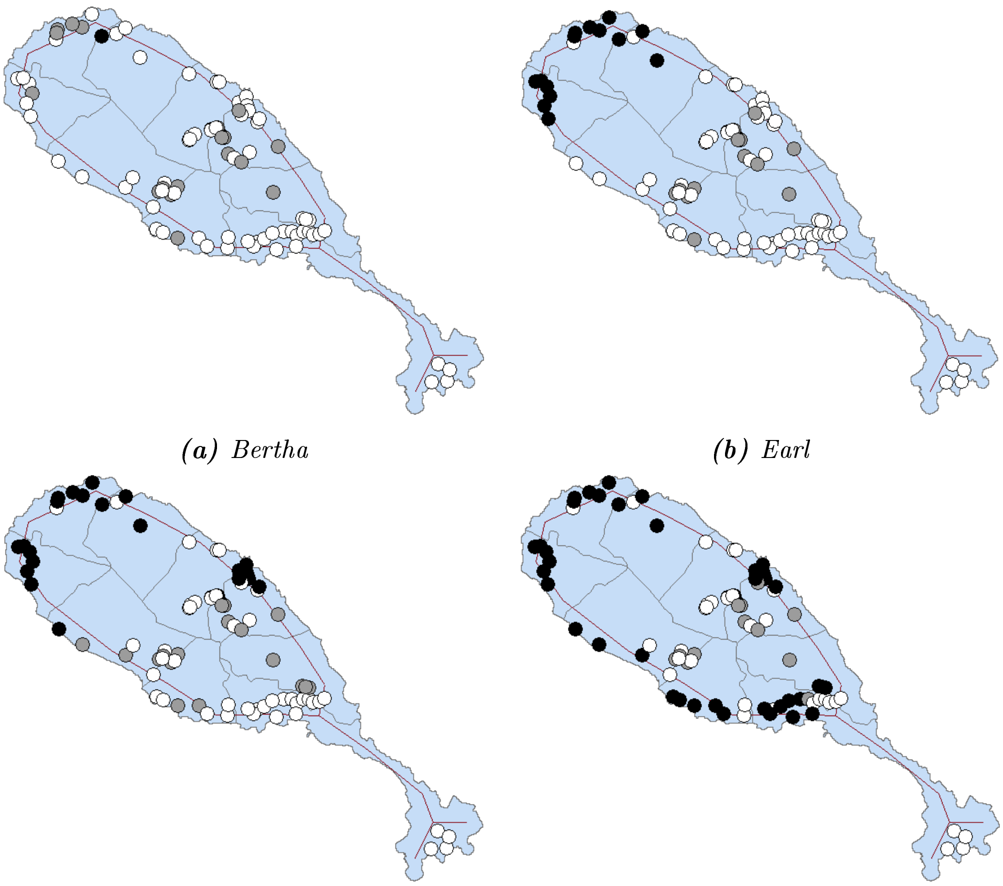
From the simulation results, Brunner et al. (n.d.) observed that the resulting average number of negative pressures correlates relatively well with the on-island wind gust. When studying the average probability of causing failure to the power system, it was observed that 10 of the 18 hurricanes had a higher probability than the minimum probability of causing at least one failure to the system. The probability of causing one failure to the system, i.e. breaking one

Table 4.2: *Results from historical hurricane simulations. From the hurricane simulations, the maximum on-island three-second wind gust speed and the average probabilities of power node failure are listed. From the power outage and water distribution modelling, the number of negative water node pressures during the 72 hour simulations are listed (Brunner et al., n.d.).*

Hurricane	**Maximum island wind gust (kts)**	**Average probability of power node failure**	**Average number of negative pressures at initial wind speed**
Georges	102.4	0.429	35.37
Donna	94.0	0.244	30.02
Hugo	89.3	0.117	26.00
Jose	89.3	0.0916	23.88
Alice	85.5	0.0524	17.54
Luis	84.3	0.102	24.37
Dog	74.5	0.0529	17.49
Earl	74.5	0.0193	12.66
Lenny	73.9	0.0143	11.09
Bertha	69.1	0.00689	6.44
Marilyn	65.0	0.00326	2.80
Debby	57.1	0.000511	0.65
Omar	56.0	0.000288	0.37
Baker	55.7	0.000180	0.11
Betsy	53.1	0.000173	0.16
Erika	41.3	5.90×10^{-6}	0.01
Irene	40.9	4.61×10^{-6}	0
Iris	29.2	6.81×10^{-8}	0

of the 157 power nodes, is 1/157, or 0.00637. Also, it was observed that 8 of the 10 most powerful hurricanes had their closest recorded track point on the northern side of the island. This shows that most of the hurricanes with the highest on-island wind speeds were particularly threatening to the Northern powerline, which in both the individual power node analysis and the parish-by-parish power outage analysis was found to be the most vulnerable powerline in the system.

Figure 4.5 shows the median water node pressures for four of the hurricane simulations; Bertha, Earl, Luis, and Georges. Brunner et al. (n.d.) chose to present the results of these hurricanes as they represented a varying degree of damage to the power and water distribution systems. The results are shown from the least powerful to the most powerful hurricane in regards of the maximum on-island wind gust, which gives a sense of how the negative pressures appears as the wind gust gets higher. Brunner et al. (n.d.) observed that the specific progression in the appearance of water node pressures mimics that of the different parish-wide outage simulations performed for multiple days. The intermediate Hurricane Earl (Figure 4.5b) shows similar patterns to breaking the middle part of the Northern powerline, while greater hurricane strengths



(a) Bertha *(b) Earl*

(c) Luis *(d) Georges*

Figure 4.5: *Schematics of the median water node pressures for historical hurricane 72-hour simulations. The different colors represent different pressure values; white represents pressures >20 psi, grey represents pressures between 0-20 psi, and black represents pressures <0 psi. The results from the following hurricane simulations are presented; (a) Bertha, (b) Earl, (c) Luis, and (d) Georges (Brunner et al., n.d.).*

show breaks similar to the St. George and St. Peter parish-wide outage simulations, where large parts of the power system broke. Even though large parts of the power system broke during the simulations of Hurricane Earl and Hurricane Luis, the western and southern parts of the island experienced few negative water node pressures. Some negative pressures started appearing in the western and southern water nodes during the simulation of Hurricane Donna, Hurricane Hugo, and Hurricane Jose, but it was not unit the most powerful hurricane, Hurricane Georges, was simulated that many negative pressures started to appear. In the simulation of Hurricane Georges, negative pressures appeared across the whole island (Figure 4.5d).

In Figure 4.6, wind speed is plotted against the average number of negative water node pressures for all historical hurricanes. The maximum number of negative pressures that appeared among the water nodes in the water distribution system during a 72-hour simulation was 39. In such cases all power nodes were non-functioning and the water distribution system had to function with its natural demand throughout the simulation. Hurricane tracks that reach the maximum of 39 negative pressures are the most dangerous tracks, as they have the potential to cause the largest damage to the power and water distribution systems. Seven of the 18 analyzed hurricanes reached that maximum potential when increasing their wind speed; Alice, Bertha, Debby, Georges, Irene, Jose, and Lenny. That Hurricane Georges had one of the most dangerous tracks was no surprise as it made landfall on St. Kitts. Among the other six hurricanes, Brunner et al. (n.d.) observed that all except Irene had tracks that were passing on the northern side of the island, which puts the Northern powerline at the highest risk of being damaged. Hurricane Irene passed on the southeastern side of the island. Based on its initial wind speed, it was one of the weakest hurricanes. However, due to its close proximity to the island it was able to generate large damages as the wind speed increased.

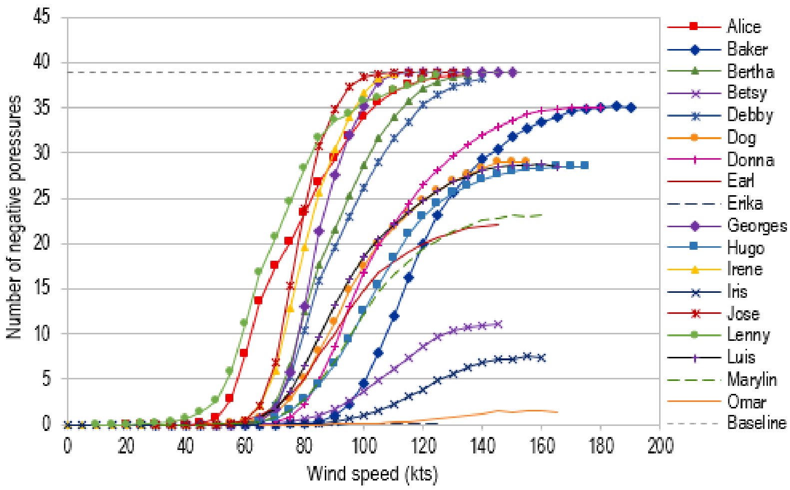


Figure 4.6: *Wind speed versus average number of negative water node pressures for historical hurricanes tracks. The baseline of 39 negative pressures is the maximum number of negative pressures that appear in the water distribution system during a 72-hour simulation when all power nodes are non-functioning (Brunner et al., n.d.).*

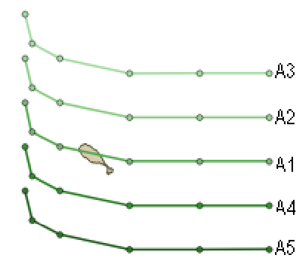
5 Description of the performed analyses

The aim of this thesis was to contribute to and extend the work by Brunner et al. (n.d.), by performing a synthetic hurricane analysis and an individual water well analysis. In the following, first a presentation of the constructed and analyzed synthetic hurricane tracks is given. Afterwards, the procedure of how the water wells were analyzed is given, as well as a description of the required modifications to the simulation models.

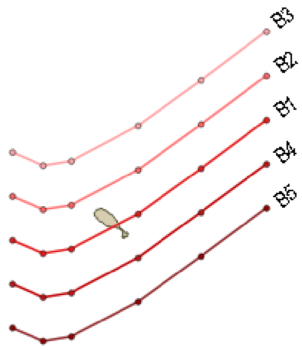
5.1 Synthetic hurricane analysis

The purpose of the synthetic hurricane analysis was to identify a potential hurricane that creates large damages to the power and water distribution system on St. Kitts, or to identify potential hurricanes that not are considered devastating hurricanes, but that nonetheless could cause surprisingly large damage to the power and water distribution system relative to the wind speed. Similar work of generating synthetic hurricanes and run these through simulation models have been performed by Berner et al. (2016). They generated the hurricanes randomly by first sample a starting location of the hurricane, and afterwards generate the movement of the hurricane by using a random forest statistical model. Each generated hurricane track was simulated at a set of different wind speeds. In this thesis, on the other hand, the hurricane tracks are not generated randomly, but constructed to behave like typical hurricanes in the Caribbean Sea. Also, in this thesis, different wind speeds were used during the simulations of each track.

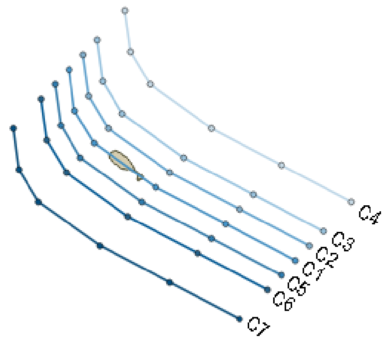
First, three different hurricane tracks that all hit central parts of the island were constructed, where one track had the most typical shape of hurricanes in the Caribbean, i.e. it moves westward while it slightly bends toward the north, named A1. The two other tracks had a similar shape as A1, but rotated in different directions when they hit land; one moving towards southwest, B1, and the other towards northwest, C1. This was done in order to study the effect of hurricanes moving in different directions. Afterwards, more tracks were constructed by shifting the three original tracks to the left and to the right in relation to the direction of the original hurricane movement in order to study the effects of different distances to St. Kitts. Both track A1 and track B1 have two tracks shifted about 33 km and 66 km both to the north (A2 and A3, and B2 and B3, respectively) and to the south (A4 and A5, and B4 and B5, respectively). Similarly, track C1 has three tracks shifted about 15 km, 31 km, and 61 km both to the northeast (C2, C3, and C4) and to the southwest (C5, C6, and C7). The different tracks are illustrated in separate figures for the A, B, and C tracks in Figure 5.1. An overview of estimated distances between the tracks and the center of St. Kitts is presented in Table 5.1, as well as to which direction the tracks were shifted compared to the original track. The estimated distances are calculated similarly as for the historical hurricanes, i.e. by calculating the minimum distance between the island and a straight line between the two closest track points. Each of the constructed hurricane tracks was simulated with wind speeds from 0-180 knots in intervals of 5-knots, and the power outage duration was set to 72 hours.



(a) A tracks



(b) B tracks



(c) C tracks

Figure 5.1: *Maps of the synthetic hurricane tracks.*

Table 5.1: *Synthetic hurricane track data including; the estimated distance between the track and St. Kitts, and the direction to the track relative to St. Kitts, i.e. at which side if island the hurricane passes.*

Track	Estimated distance between track and the center of St. Kitts (km)	Direction the track was shifted compared to original track
A3	66	N
A2	33	N
A1	0	-
A4	32	S
A5	65	S
B3	50	N
B2	21	N
B1	8	-
B4	38	S
B5	66	S
C4	60	NE
C3	30	NE
C2	14	NE
C1	0	-
C5	16	SW
C6	32	SW
C7	62	SW

5.2 Individual water well analysis

The purpose of the individual water well analysis was to identify the most critical linkages between the power system and the water distribution system. The linkages between the systems are the wells as they require electrical power to pump water into the distribution system. The analysis was performed by removing the dependency on electric power for one well at the time. One way to do this in real life could be to install a stand-by power generator with sufficient fuel at the site where a well is located. Thus, when that well is affected by a power outage, the stand-by generator can be switched on to supply the well with electricity. The well is thereby no longer dependent on the power system to maintain normal operation. For each well that the dependency on the power system was removed, the simulations were run with the worst-case hurricane track. The results were compared to the base case where all wells were dependent on the power system, to identify the well(s) that gives the biggest reduction in number of negative water node pressures. Prior to running the simulations, the power outage model required modifications. The removed dependency between a well and its connected power node was simulated by changing the status of the connected power node to 'functioning' during power outages. For *Menu option 1: Create lookup table* (see Section 3.3.1), this meant changing the status of the connected power node to always be functioning after the code had identified all possible scenarios of non-functioning power nodes. All downstream power nodes along the powerline of the wells connected power node were not affected, and would still be non-functioning. Later, when the model determined the different combinations of non-functioning water wells from the scenarios of non-functioning power nodes, the water well(s) with removed dependency on the power system was set as functioning during the water distribution modeling in EPANET for all scenarios. In *Menu option 2: Run hurricanes based off of hurricane probabilities* (see Section 3.3.2), the power node connected to the well with removed power system dependency was set to be functioning for all iteration scenarios in the generated binary adjacency matrix that showed the functionality of all power nodes. By doing that, the water well with removed power system dependency would always be functioning and never included in the scenarios of non-functioning water wells. Thus, a matching scenario could be found when looking up the scenarios in the lookup table generated in Menu option 1 in order to record the resulting water node pressures.

Among the power nodes with water wells connected to them, all except two had only one connected well. Among the remaining two power nodes, one had two water wells connected to it; well 52 and well 53 (see Figure 3.2 for illustration of the water distribution system with labeled water well id's), while the other had three connected water wells; wells 36, 38, and 39. This means that all 31 wells except these five were analyzed individually, while these five wells had to be analyzed in two groups together with their neighbor wells; 52 and 53 in one group, and 36, 38, and 39 the other group.

6 Results

6.1 Synthetic hurricanes analysis results

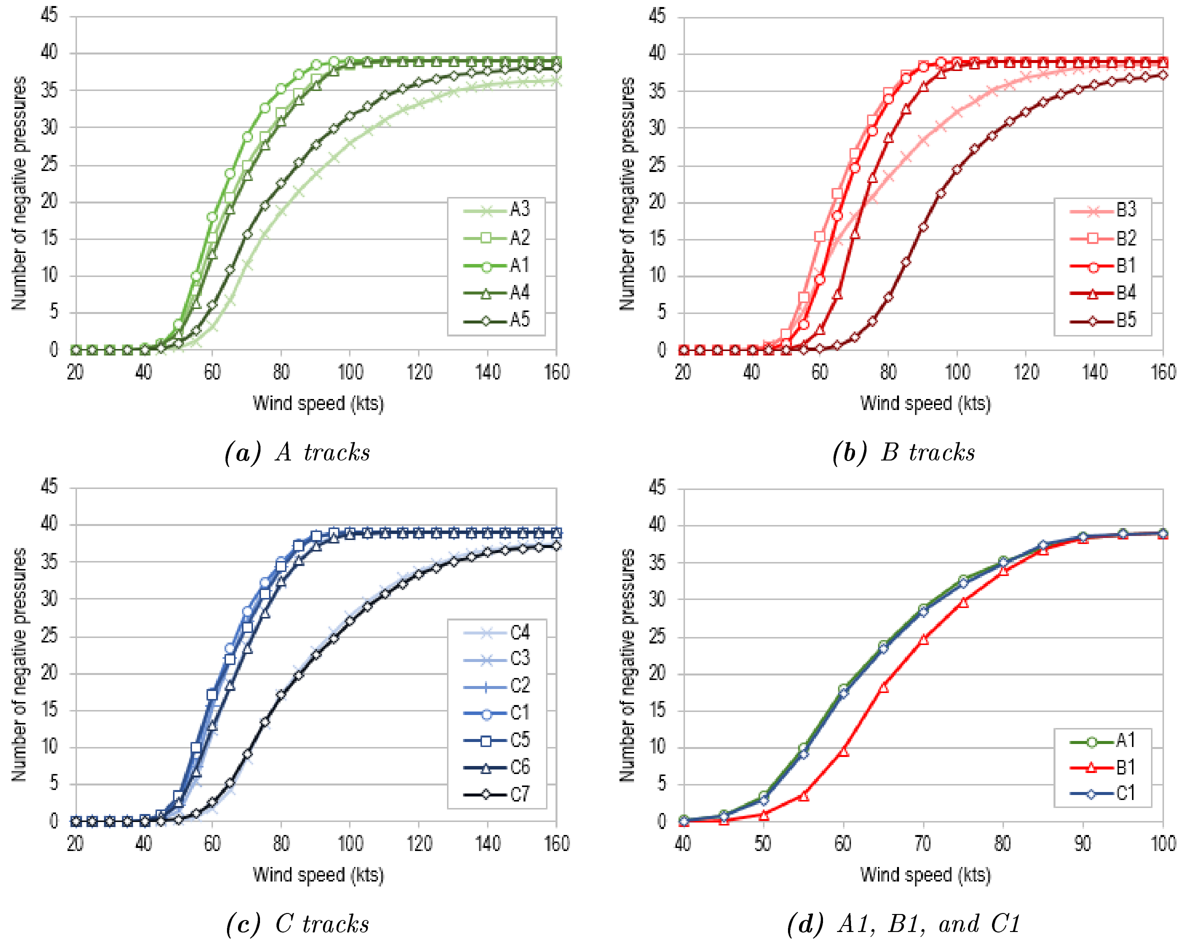
The resulting average number of negative water node pressures versus wind speed for each synthetic hurricane simulation are presented in Figure 6.1. The results for the A, B, and C tracks are plotted in separate figures; Figure 6.1a, 6.1b, and 6.1c, respectively. Within each figure, the darkness of the colors of the curves represents the location of the tracks, where the tracks are sorted from the most northernmost track to the most southernmost track with increasing darkness. Figure 6.1d zooms in on the three tracks that hit St. Kitts, i.e. A1, B1, and C1, in order to make it easier to compare the different track movements with each other. When studying the figures, it can be observed that all tracks have the potential to cause large damages to the power and water distribution systems for high hurricane wind speeds. Most of the tracks reach the maximum potential of 39 negative pressures at a wind speed of about 100 knots. The remaining tracks, i.e. A3, A5, B3, B5, C4, and C7, never reached a plateau for the simulated wind speeds, but the curves for these tracks seem to go toward values close to the maximum potential. These tracks that does not reach this maximum potential at 100 knots have in common that they are the tracks passing St. Kitts furthest away from the island.

There seem to be a correlation between the average number of negative pressures and the estimated distance to the center of the island, especially when studying the C tracks (Figure 6.1c). Track C1, which hit St. Kitts, is the most damaging track closely followed by C2 and C4, which both passed the island with an estimated distance of about 15 km. The results of track C2 and C5 are almost identical to the result of track C1, with the exception of a slightly lower number of negative pressures at wind speeds between 60 and 80 knots. Furthermore, tracks C3 and C6, which both passed the island with an estimated distance of about 31 km, follows with almost identical numbers of negative pressures that are slightly lower than the values of C1, C2, and C5. Finally, track C4 and C7 are the least dangerous tracks among the C tracks. These tracks also obtained almost identical results and are passing St. Kitts with almost the same estimated distance from the island of about 61 km.

The correlation between the average number of negative pressures and the estimated distance to the center of the island can also be observed in the results of the A tracks (Figure 6.1a). Also for the A tracks, the track that hit the island, i.e. track A1, is the most devastating track closely followed by A2 and A4, while the tracks further away from the island, i.e. A3 and A5, where the least devastating tracks. However, the results do not show the same perfect symmetry regarding almost identical number of negative pressures for tracks with almost the same estimated distance to the island as the result from the C tracks shows, but the curves of A2 and A4 show the same trend as C4 and C7, which were also passing the island at the furthest distance.

The results of the B tracks (Figure 6.1b) differ from the results of the A and C tracks by that track B2, which passed the island at an estimated distance from the center of the island of 21 km, is more devastating than track B1, which hit the island at a distance from the center of 8 km. In addition, track B3, which is one of the tracks that passed the island furthest away, is equally devastating as track B1 at wind speeds of 60 knots and lower. Track B4 and B5, on the other hand, behaved similar as the A and C tracks, with corresponding distances to the island. In the case of the B tracks, the tracks passing the island on the northern side of the island were more devastating than the tracks passing on the southern side. Thus, on which side the track passes the island seems to affect the results.

When comparing the tracks that hit the island, i.e. tracks A1, B1 and C1 (Figure 6.1d), it can be observed that track A1 and track C1 have almost identical results, where A1 has a slightly higher number of negative pressures between 40 and 80 knots. For track B1, the number of negative pressures are significantly lower than A1 and C1, where the largest difference is about 8 negative pressures at simulations with a wind speed of 60 knots. Possible explanations for the difference between the results for these tracks are that the hurricane movement directions are different as the tracks hit land, or that B1 crosses St. Kitts at the southern part of the island, while A1 crosses the island further north and C1 crosses the whole length of the island.



***(a)** A tracks*

***(b)** B tracks*

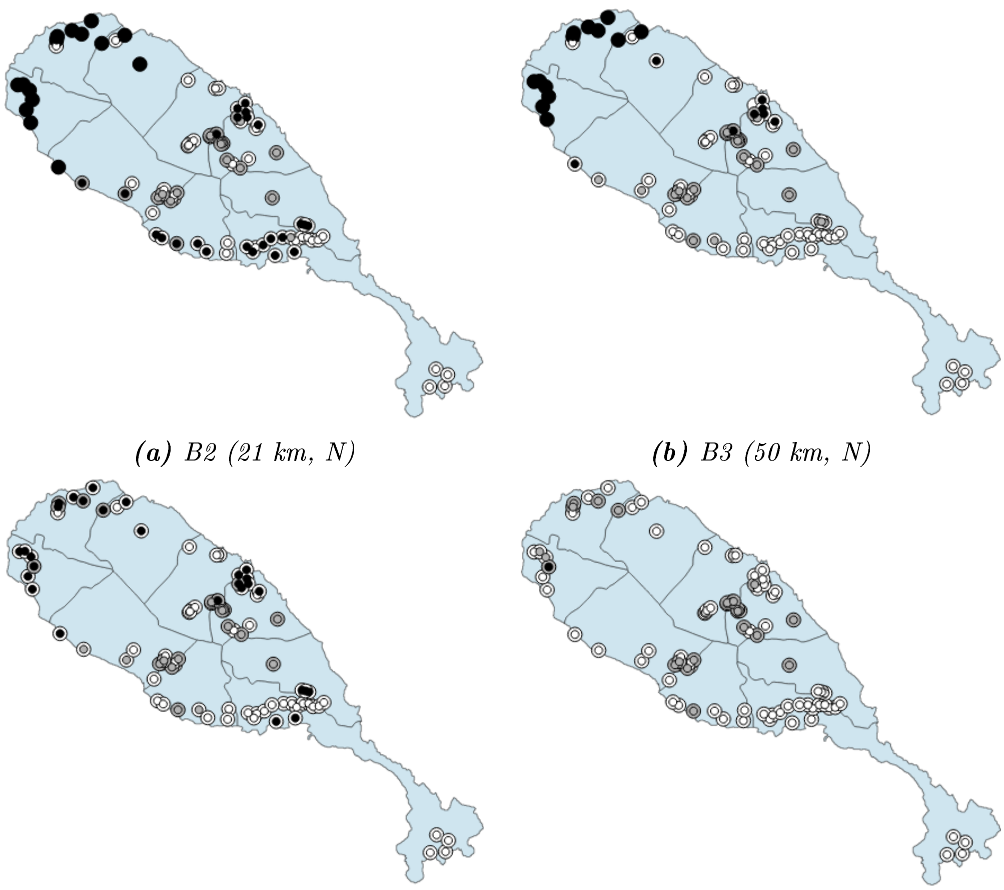
***(c)** C tracks*

***(d)** A1, B1, and C1*

***Figure 6.1:** Wind speed versus number of negative water node pressures for synthetic hurricane tracks. Figure (a) shows A tracks, (b) B tracks, (c) C tracks, and (d) zooms in on tracks A1, B1, and C1, which were the tracks that hit St. Kitts.*

The median pressures for the water nodes from all iterations were analyzed for each of the synthetic tracks at wind speeds of 60, 80, and 130 knots in order to see if these results could provide more information. At wind speeds of 130 knots, most power nodes broke along the entire distribution system for all the tracks, similarly as for the historical hurricane simulation of Hurricane Georges (Figure 4.5d). Thus, at 130 knots all the constructed synthetic hurricane track caused large damages. For the wind speed of 60 and 80 knots, on the other hand, variations in damages were observed. The correlation between damages and distances between the tracks and the island seen in Figure 6.1, was also observed in these results. At wind speeds of 60 and 80 knots, the number of median pressures that were negative decreased as the track distances to the island increased. The only exception was B2, which had a couple of negative pressures more than B1. Also, the symmetry observed in Figure 6.1a and 6.1c, i.e. that A and C tracks with the same distances to the island had almost identical results, was observed for A and C tracks in these results. For the tracks that had approximately the same distances to the island, but which passed the island on opposite sides, almost the same water nodes were observed to result in negative pressures. For instance, for both track A2 that passed about 33 km to the north of the center of the island and track A4 that passed about 32 km to the south of the center of the island, the same negative pressures appeared in the northern part of St. Kitts during simulations at a wind speed of 60 knots. At a wind speed of 80 knot some additional negative pressures appeared at the east coast and in the south for both tracks. These results were similar to the damages caused by Hurricane Luis (Figure 4.5c).

For the B tracks, this comparison could not be made because the distances between the tracks are not symmetrical to the center of the island. While both track A1 and C1 hit the center of the island, track B1 hit the island about 8 km to the south of the center. The distances to the remaining B tracks are symmetrical to B1, and not to the center of the island. From Table 5.1 it can be read that the estimated distances between the remaining B tracks and the center of the island are as following; B2 = 21 km, B3 = 50 km, B4 = 38 km, and B5 = 66 km. Figure 6.2 presents the median water node pressures during the simulations of track B2, B3, B4, and B5 at wind speed of 60 and 80 knots, where the outer circle represents the pressures at 60 knots, and the inner circles the pressures at 80 knots. The pressure values are color coded, where white represents pressures >20 psi, grey represents pressures between 0-20 psi, and black represents pressures >0 psi. In the parentheses in each figure captions, the estimated distance between the track and the island as well as the direction the track was shifted compared to track B1 is presented. Studying Figure 6.2b and 6.2c, it can be observed that while track B3 have negative pressures appearing in the northern part of the island at a wind speed of 60 knots, no negative pressures appeared for track B4 at 60 knots. At a wind speed of 80 knots, on the other hand, negative pressures appeared in the north and on the eastern coast for both tracks B3 and B4. In addition, track B4 has some negative pressures appearing in the southern part of the island at 80 knots. Thus, also when studying the median water node pressures for B tracks, no clear correlation between damages and track distances to the center of the island can be observed. However, an interesting observation can be made from the results of the B tracks simulations; when comparing track B2 and B3 that passed on the northern side of the island with track B4 and B5 that passed on the southern side, it can be observed that B2 and B3 generally results in



(a) B2 (21 km, N) *(b) B3 (50 km, N)*

(c) B4 (38 km, S) *(d) B5 (66 km, S)*

Figure 6.2: *Schematics of the median water node pressures for the synthetic tracks B2 (a), B3 (b), B4 (c), and B5 (d) at wind speeds of 60 and 80 knots, where the outer circle represents the median pressures at a wind speed of 60 knots and the inner circle at a wind speed of 80 knots. The different colors represent different pressure values; white represents pressures >20 psi, grey represents pressures between 0-20 psi, and black represents pressures <0 psi. Track distance to the center of St. Kitts and the direction to the track relative to the island are showed in the captions below each figure.*

more negative pressures in water nodes in the northern parts of the island than B4 and B5. As concluded for the B track results in Figure 6.1b, also in these results the direction to the track relative to the island seem to influence the resulting damages.

6.2 Individual water well analysis results

In the individual water well analysis, the synthetic track A1 was used as the worst-case hurricane track. Track C1 could also had been used, as it was equally damaging as track A1, but track A1 was chosen as it had the most typical track shape of hurricanes in the area. In the analysis of track A1, where the dependency on the power system was removed for one well at the time, five unique results appeared. One result showed that the average number of negative pressures reached the maximum potential of 39, i.e. no improvement compared to the original simulation of track A1 where all wells were dependent to the power system, while for the remaining four results the negative pressure reached a plateau at the following numbers; 34, 29, 28, and 27.

The number of negative pressures reached these plateaus when the entire power system was non-functioning, and no wells except the analyzed well with the removed dependency to the power system were functioning.

All five results are presented in Figure 6.3, where the wind speed is plotted against the average number of negative pressures for the original simulation of track A1 and for the analyses where water well 4, well 13, well 16, and well 28 had their dependency on the power system removed. The result of track A1 represents no improvement, i.e. no reduction in the number of negative pressures, while the result of well 4, well 13, well 16, and well 28 represents the results where the number of negative pressures reach a plateau of 34, 27, 28, and 29 negative pressures, respectively. For wells reaching the same plateau of number of negative pressures, the results followed more or less identical curves in the plot. The only exception was for well 13 compared to the other wells also reaching a plateau of 27 negative pressures, which were the following six wells; 12, 15, 19, 21, 22, and 23. While well 13 showed a reduction in the number of negative pressures at low wind speeds between 45 and 65 knots, the other six wells followed the same curve as the original simulation of track A1 at wind speeds below 65 knots. Another well that also showed a reduction in the number of negative pressures at lower wind speeds, was well 4, which was the only well reaching a plateau of 34 negative pressures. At all wind speeds, well 4 showed improvements compared to the original simulation of track A1, and at wind speeds ranging from 60 to 70 knots, well 4 had the lowest number of negative pressures among all the wells. A possible reason for why well 4 and well 13 showed a reduction in the number of negative pressures at lower wind speeds is that these two wells have the largest water productions among all wells of 92 and 102 gallons per minute, respectively. Thus, high production volumes in the analyzed wells seem to influence the resulting average number of negative pressures at lower wind speeds.

An overview showing the resulting number of negative water node pressures reached in each of the simulations where one well at the time had their dependency to the power system removed

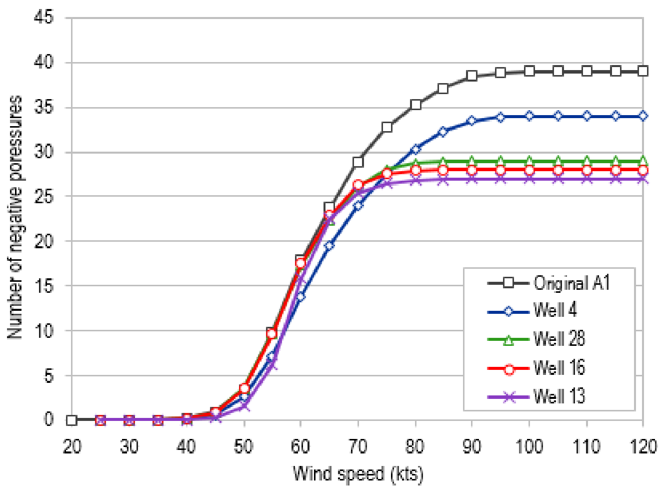


Figure 6.3: *Wind speed versus average number of negative water node pressures for track A1 for different scenarios were the following water wells have back-up power in case of power outages lasting 72 hours; 4, 13, 16, and 28.*

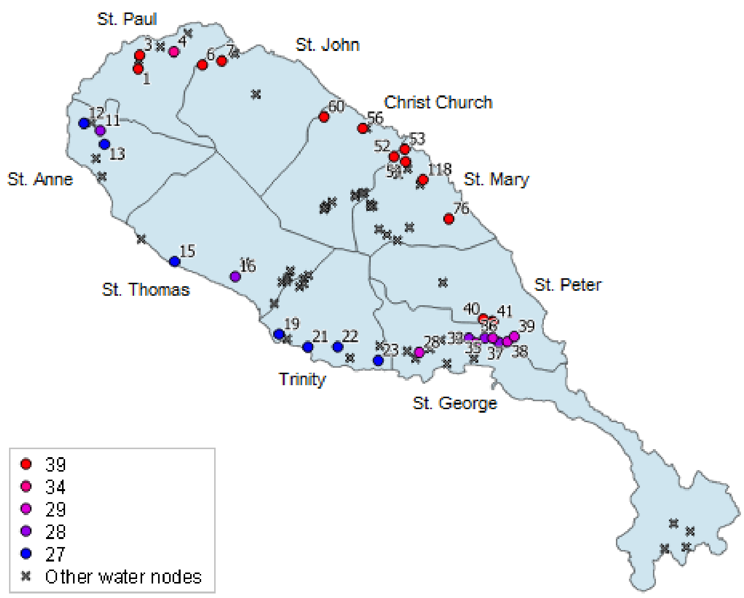


Figure 6.4: *Schematics showing the resulting number of negative water node pressures reached in each of the simulations, where one well at the time had access to back-up power during power outages. The wells are represented by color coded circles (with labelled well id's) where the color presents the resulting number of negative pressures; with a color scale ranging from red (39 negative pressures) to blue (27 negative pressures). Crosses represent the remaining water nodes in the system.*

is presented in Figure 6.4. The wells are represented by color coded circles where the color presents the resulting number of negative pressures; with a color scale ranging from red (39 negative pressures) to blue (27 negative pressures). The remaining water nodes in the system are represented by crosses. Studying this figure, it can be observed that there is a clear difference in the results obtained by removing the dependency on the power system of a well on the west coast compared to the east coast of the island. The wells on the western side of the island reach a plateau of 27 or 28 negative pressures, while all wells on the eastern side, except well 4, showed no reduction in the number of negative pressures compared to the base case. In the area around the capital of Basseterre, the wells reached a plateau of 28 or 29 negative pressures. Thus, from these results, the wells along the western coast have the largest potential to reduce the potential damages to the water distribution system.

Some wells were analyzed together in groups because the wells within each group were supplied with electricity from the same power pole. These wells were wells 52 and 53 in one group, and wells 36, 38, and 39 in another group. Although these wells were analyzed together, no significant reduction in the number of negative pressures were observed compared to the neighbor wells that were analyzed individually. Wells 52 and 53 reached a plateau of 39 negative pressures, i.e. no improvements compare to the base case, similar to the neighbor wells on the east coast. Wells 36, 38, and 39 reached a plateau of 29 negative pressures, which was similar to the result of the neighbor wells. Thus, being analyzed together in groups does not seem to have given these wells any significant advantages.

When studying which wells that most frequently lose their power supply and consequently becomes non-functional, it becomes clear that the wells located in the parishes of St. Anne and

St. Paul are the most affected wells in almost every simulation performed in this case study. These wells include wells 1, 3, 4, 6, 7, 11, 12, and 13. These results can easily be explained by that all these wells are connected to the last part of Northern powerline that is the largest among the three modelled powerlines as it encompasses almost half of the island. In practice, this means that these wells are particularly exposed to power outages as the power nodes supplying them are affected by the status of all preceding power nodes along the powerline. To summarize the results of the individual water well analysis, it can be concluded that well 13 is one of the most critical wells in the system. The reasons are that well 13 overall showed the best potential to reduce the average number of negative pressures when removing its dependency on the power system, well 13 has the highest production capacity in the system, and well 13 was one of the wells that most frequently were affected by power outages. In order to study the effect of removing the dependency on the power system of well 13 more closely, additional simulations of well 13 were performed for power outage durations of 12, 24, and 48 hours. Together with the previous 72-hour simulation results, these results were compared to the base-case simulations of track A1 where all wells were dependent on the power system. The results are presented in Figure 6.5, where the base-case simulations of track A1 are represented by solid lines and the simulations where well 13 had its dependency on the power system removed are represented by dashed lines. The different power outage durations are represented with different colors; 72 hours with blue, 48 hours with green, 24 hours with red, and 12 hours with purple. Two main observations can be made in the figure. First, it can be observed that by reducing the duration of the power outage, the number of negative water node pressures reduces significantly. When studying the original simulations of track A1, for instance, it can be observed that if the power system is repaired to be up and running as normal after 12 hours, the number of negative pressures is only 2 at high wind speeds compared to 39 during 72-hour outages. If the power outage lasts 24 hours, the number of negative pressures is 11, and for a power outage lasting 48 hours, the number of negative pressures if 24. Thus, the potential damages to the water distribution system can be significantly reduces by fixing the power system as fast as possible.

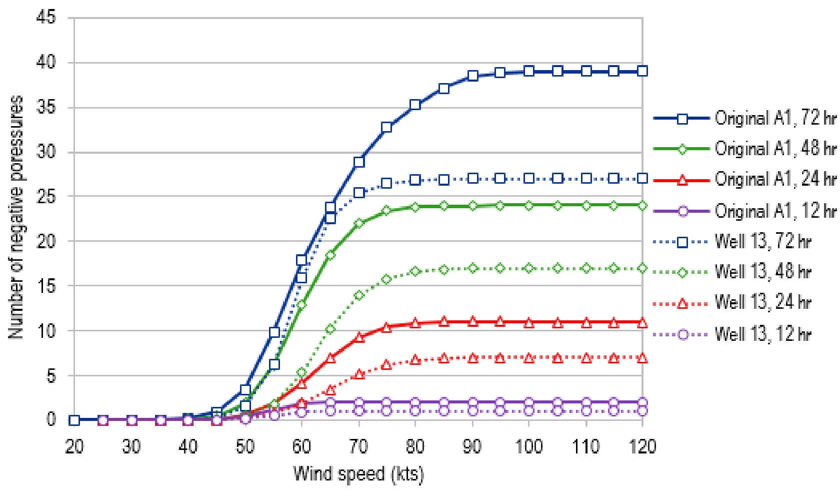


Figure 6.5: *Wind speed versus average number of negative water node pressures for the original simulation of track A1 (solid lines) compared to the scenario where well 13 had removed dependency on the power system (dashed lines) for power outages lasting 72 hours (blue), 48 hours (green), 24 hours (red), and 12 hours (purple).*

Secondly, when well 13 has its dependency on the power system removed, the number of negative pressures is significantly reduced compared to the base-case scenario for all simulations by 12, 7, 4, and 1, for the 72-hour, 48-hour, 24-hour, and 12-hour simulations, respectively. Thus, if it is possible to remove the dependency on the power system for well 13 by for instance installing a stand-by power generator at the site of the power pole supplying this well with power, it can reduce damages to the water distribution system significantly for power outages also lasting for shorter periods than 72 hours.

7 Discussion

By modelling the performance of the power and water distribution systems on St. Kitts during hurricane activity, vulnerabilities in the power and water distribution system as well as potentially devastating hurricanes were identified. First, findings from the results of the analyses performed in the case study will be discussed. Afterwards, suggestions are given of possible upgrades of the power and water distribution systems as well as of preventative measures that can be implemented.

7.1 Powerline vulnerabilities

Both the individual power node analysis and the parish-by-parish outage analysis performed by Brunner et al. (n.d.) showed that the Northern and Southern powerlines were more vulnerable than the Western powerline. In the individual power node analysis, power outages lasting 24 hours were simulated. The results showed that breaking any single power node along the Western power line had no effect on the water distribution system (see Figure 4.1). In comparison, negative pressures appeared in the distribution system for almost every single power node failure along the Northern powerline and for four of the power nodes along the Southern powerline.

The reason that the distribution system manages to cope without the contribution from the wells connected to the Western powerline during a 24-hour simulation is that the Western powerline supplies the smallest number of wells among the three powerlines. When studying the distribution system more closely, it also becomes clear that the area where the Western powerline is located has the lowest water demand compared to the areas where the Northern and Southern powerlines are located. This area also has the fewest amount of storage tanks, but one reservoir source enters the system in this area, and two reservoir sources enter the system in the south of the western coast. Thus, there is not a complete loss of water even if the wells do not pump water into the system.

The reason almost every single power node failure along the Northern powerline resulted in negative pressures appearing in the distribution system is that the powerline is the longest powerline that occupies more parishes and supplies more wells with electricity than the other powerlines. The number of wells connected to the Northern powerline is 15 out of a total of 31 wells in the system. Thus, when a power node in the beginning of the powerline fails and all downstream power nodes becomes non-functional, all 15 wells lose their power supply and can no longer pump water into the distribution system. In such a case, is it easy to understand that negative pressures occur in the distribution system. But from Figure 4.1 it could be observed that the single failure of all power nodes except the last two nodes resulted in negative pressures appearing in the distribution system. This means that even in cases where the third last power node fail and only one well becomes non-functional, the distribution system is affected and negative pressures appears. This well, which is connected to the last part of the Northern powerline, is well 13. In the individual water well analysis, well 13 was found to be one of the most critical wells in the system. Although well 13 has two neighbor wells and three storage tanks located in close proximity, the distribution system does not manage to cope without its contribution during a 24-hour simulation. The reason is likely due to the fact that well 13 has the highest production capacity among all the wells in the system with a production of 102 gallons per minute. When studying the water distribution system of St. Kitts (see Figure 3.2), it can be observed that there is only one reservoir source in the northern parts of St. Kitts. Although there are some storage tanks installed in the north, they are not alone able to provide the water demand to the area when the wells are non-functional.

In the 24-hour simulation, single failure of four of the power nodes in the Southern powerline resulted in negative pressures in the distribution system. These four nodes were all located in the main city of Basseterre, which has a high demand. The results from the 12-hour simulations were different, as no negative pressures appeared when breaking any of these four power nodes. These results show that the distribution system manages to cope without the contribution from the affected wells during a 12-hour period, but not during a 24-hour period. This means that the storage tanks and reservoir sources only manage to meet the water demand for a short period.

The powerline vulnerabilities discussed above were also evident in the simulation results of power outages lasting for longer times, i.e. the result of the parish-by-parish outage simulations lasting 48 and 72 hours. During the maximum outage duration of 72 hours, power outage of the Western powerline (simulated by breaking the power nodes in the parish of Trinity) only resulted in two negative pressures in the distribution system, while power outage of the Northern and Southern powerlines (simulated by breaking the power nodes in the parishes of St. Peter and St. George, respectively) resulted in a high number of negative pressures. While the outage of the Northern powerline resulted in small differences in negative pressures between the 48-hour and 72-hour simulations, the Southern powerline appears to become more important when the outage duration increases from 48 to 72 hours as the number of negative pressures had a significant increase. This confirms the discussion above, that the water supply from storage tanks and reservoir sources becomes less efficient as times goes on.

7.2 The effect of different power outage durations

As discussed above, the duration of the power outages is an important factor in the number of negative pressures appearing in the water distribution system during the simulations, especially for power outages in the southern parts of St. Kitts. This importance regarding the duration of the power outages was also observed for outages that were affecting the entire island, i.e. when all three powerlines were non-functioning at the same time. When studying the maximum potential regarding the average number of negative pressures for the synthetic track A1 (Figure 6.5), the following differences were observed during the simulations; 2 for the 12-hour simulation, 11 for the 24-hour simulation, 24 for the 48-hour simulation, and 39 for the 72-hour simulation. Thus, although track A1 simulated one of the worst-case hurricanes to hit St. Kitts and the entire island lost its power supply during the simulations at high wind speeds, the results showed that the number of negative pressures appearing in the distribution system during the short-term analyses were significantly lower than during the long-term analyses.

These results confirm the previously discussed results, that the water supply from storage tanks and reservoir sources becomes less efficient as times goes on. During 12-hour power outages, water from the storage tanks and reservoir sources help to keep the number of negative pressures at a relatively low number. But as the input water from the storage tanks and reservoir sources does not meet the water demand, the number of negative pressures increases as the duration of the outages increases. Hence, St. Kitts is dependent on the functionality of its wells to avoid negative pressures occurring in the distribution system. Therefore, in case of power outages, the shorter time it takes to get the wells back to normal operation, the less lack of water supply and potential damages to the distribution system can be expected.

7.3 Critical linkages between the power and water distribution systems

In the individual water well analysis, the linkages between the power and water distribution systems were studied, i.e. the wells as they require electricity to function. The remaining water distribution system is gravity fed. In the analysis, simulations of the synthetic track A1 were performed where one well at the time had their dependency on the power system removed. From the results, the lowest number of negative pressures was obtained for the simulations were one of the wells along the western coast of the island had its dependency on the power system removed, i.e. one of the wells in the parishes of Trinity, St. Thomas, and St. Anne (see Figure 6.4). The wells along the western coast were closely followed by most of the wells in and around the main city of Basseterre, while almost all the wells along the eastern and northern coast showed no reduction in the number of negative pressures compared to the base case were all wells were dependent on the power system. The only exception was well 4 that resulted in a small decrease in the number of negative pressures.

Considering that the water demand in the parishes of Trinity and St. Thomas is low and that the wells in these parishes are supplied with electricity from the Western powerline, which was found to be the least vulnerable powerline, it was unexpected that the results indicated that the wells in these parishes are among the most critical wells. It was also unexpected that most of the wells in the parishes of St. Paul and St. John did not show any reductions in the number of negative pressures, while the wells in the neighbor parish of St. Anne were among the most critical ones. The total water demand in these three northern parishes is high and the water inflow from reservoir sources is low. Therefore, it was expected that the wells in all three parishes would turn out to be critical for the distribution system, and not only the wells in St. Anne.

A possible explanation for these results is the low concentration of storage tanks along the entire western side of the island compared to the eastern side, and the high inflow of water from reservoir sources on the eastern side. There are three large reservoir sources located in the parishes of St. Mary and Christ Church. The highest water demand is in and around in the city of Basseterre, followed by the northernmost areas of the island. Therefore, when all wells stop functioning due to power outages, the water in the western and eastern parishes will flow both to the north and the south to help supplying the high demand areas. While the eastern parishes have high inflow of water from the reservoir sources, the western side does not have sufficient inflow of water, which results in pressure drop inside the distribution system along the western coast. By removing the dependency on the power system of one of the most critical wells along the western coast, the water produced by that well has the potential to avoid up to 12 negative pressures to occur in the system. Among the nine wells located in the western parishes of Trinity, St. Thomas, and St. Anne, seven of them resulted in being equally critical. In the results for these wells, 27 negative pressures appeared, which was the largest reduction of 12 negative pressures compared to the base case. The two remaining wells were well 11 and well 16, which both resulted in 28 negative pressures.

In the above discussion, it is important to remember that the wells along the western coast are only found to be the most critical wells in the situations where the entire island is affected by power outages and all wells lose their power supply. In the situations where the simulations were run at lower wind speeds and only parts of the power system failed, the results showed that only two wells had the potential to reduce the number of negative pressures compared to the base case. These wells were well 4 and well 13, and they were the two wells with highest water production among all wells on the island. In addition, both wells are connected to the last part of the Northern powerline, which is the part of the power system that most frequently experienced outages during all simulations performed in the case study. Well 13 is located in the parish of St. Anne and is one of the wells included in the most critical wells discussed above. Therefore, it is natural to conclude that if for instance it is possible to installing a stand-by generator on St. Kitts in order to remove the dependency on the power system for one well, the generator should be installed at the location of the power pole that supplies well 13 with power.

If it is possible to install more than one stand-by generators, two options should be evaluated; either install the second generator to support one of the western coast wells with back-up power, or install it to supply well 4 with back-up power. During extreme weather when the entire power system fails, the distribution system will gain the most of having it installed to support one of the wells along the west coast. But the Northern powerline was found to be the most vulnerable powerlines in situations where only parts of the power system fails, and the last part of this powerline is the part of the power system fails most frequently. As well 4 is connected to the last part of the Northern powerline, installing a stand-by generator to support well 4 with back-up power will perhaps be more beneficial for the distribution system in the long run. But as the only one linkage between the power and water distribution system was analyzed at the time in this case study, a conclusion of whether to install a second stand-by generator at the side of well 4 or at the site of one of the wells along the western coast cannot be made from these results. Additional analyses where two linkages are analyzed together should be performed before making such a conclusion.

7.4 Factors affecting the simulated damages caused by hurricanes

In both the historical hurricane analysis and the synthetic hurricane analysis, many of the simulated hurricane tracks reached the maximum potential of 39 negative water node pressures during a 72-hour simulation at high wind speeds of 100 knots and higher. This potential corresponds to the situation where the entire power system has failed. This means that many different hurricane tracks can cause a worst-case scenario for the power and water distribution system if the wind speed is high. Generally, the results showed that almost all the simulated hurricane tracks have the potential to cause significant damages at high wind speed. In this section, the simulated hurricane tracks will be studied more closely and factors that causes some of these to be more devastating than the others will be discussed. In the end, a conclusion will be given about which hurricanes that are most threatening to St. Kitts.

7.4.1 Distance between the hurricane track and the island

When Brunner et al. (n.d.) analyzed the results of the historical hurricane simulaitons they performed, they discovered that 8 out of the 10 historical hurricanes that resulted in the strongest on-island wind gust during the simulation at original wind speeds, passed the island in the northern side. Hurricane Georges made landfall, which means that only one of the 10 hurricanes, Hurricane Irene, passed on the southern side of the island. This means that most of the strongest hurricanes of the past have been particularly threatening to the Northern powerline, which was found to be one of the most vulnerable powerlines. Brunner et al. (n.d.) concluded that these hurricanes had a higher potential to damage the power system simply because of their orientation to the island, which they pointed out that also was confirmed in the results presented in Figure 4.6. Studying the results of Figure 4.6 more closely, it is true that most of the hurricanes that passed the island on the northern side of the island resulted in a higher number of negative pressures in the distribution system. But by also comparing the results with the estimated distance between the island and the tracks, it becomes clear that the most damaging hurricanes also were the hurricanes that were passing closest to the island. Brunner et al. (n.d.) only calculated the distance between the recorded track points and the center of the island, and as the closest track point for a hurricane was not necessarily recorded at the time the hurricane actually was closest to the island, these distance values gave an incorrect picture of which hurricanes that had the shortest distance to the island. The estimated distance values, which for each hurricane was estimated by calculating the minimum distance between the island and a constructed straight line between the two closest recorded track points, provide a better picture of the actual minimum distances, and the results in Figure 4.6 also correlated well with these estimated distances. For instance, all hurricanes that reached the maximum potential of 39 negative water node pressures (Georges, Irene, Jose, Lenny, and Alice) passed the center of the island within a radius of 46 km. Hurricane Erika and Hurricane Omar, which made the least damages for all simulated wind speeds, passed the island furthest away at an estimated distance of 216 km and 148 km, respectively. Thus, from the result of the historical hurricanes it is difficult to make any conclusions regarding the importance of the orientation of the tracks relative the island.

The good correlation between simulated damages and estimated minimum distance to the center of the island were also observed in the synthetic hurricane analysis, especially for the A and C tracks. The C tracks showed the best correlation, where tracks that had about the same estimated distance to the island had almost identical curves in the figure where the average number of negative pressures were plotted against wind speed (Figure 6.1c). For the B tracks, on the other hand, no good correlation was found between the simulated damages and the estimated distances to the island. For instance, track B2 that passed the island about 21 km to the north of the island was found to be more damaging than track B1 that hit the island (Figure 6.1b). Similarly, track B3 was more damaging than B4, and their estimated distances were 50 km and 38 km, respectively. In the Results section (Section 6.1), it was mentioned that the results of the B tracks simulations seem to be affected by whether the tracks are passing on the northern or the southern side of the island. A possible explanation for this is that tracks that are passing on the northern side of the island are closer to the vulnerable parts of the power system, i.e. the Northern powerline, than tracks that are passing the island about the same distance away but on the southern side of the island. New estimated distances between the track and the island are calculated, but this time they are calculated from a point in the north of the island instead of the center point. These are presented in Table 7.1 together with a ranking of the most devastating tracks from the results presented in Figure 6.1b at wind speed above 70 knots. When estimating the distances to the north of the island instead of the center, track B2 is now the track that with the smallest estimated distance of 12 km among the B tracks, followed by B1, B3, B4, and B5, with distances 16, 43, 47, and 76, respectively. By ordering the B tracks from most damaging to least damaging, almost the same order is obtained. The only exception if the ranking of B3 and B4. But, from Figure (6.1b, it can be observed that B3 was more damaging than B4 at wind speeds below 70 knots. From this is can be concluded that the closer the hurricanes are to the North of St. Kitts, the higher is the potential for damages to the power system.

Table 7.1: *Estimated distance between B tracks and the north of St. Kitts.*

Track	**Estimated distance between track and the north of St. Kitts (km)**	**Ranking of the most devastating tracks from the results presented in Figure 6.1b at wind speed above 70 knots**
B1	16	2
B2	12	1
B3	43	4
B4	47	3
B5	76	5

This conclusion can be made for the A and C tracks also. As track C1 is moving through the northern parts of the island and track A1 is moving close to the northern parts, the estimated distance between the tracks and the north of the island will be the same for the C tracks and almost the same for the A tracks as the estimated distances calculated between the tracks and the center of the island. Therefore, also for the A and C tracks, the estimated distance correlates well with the simulated damages.

7.4.2 Hurricane movement direction and wind speed development

By studying the hurricane tracks in the historical hurricane analysis, it can be observed that although there is a correlation between the estimated distances between the tracks and the island and the simulated damages, the correlation is not as good as for the synthetic hurricane simulations. In Figure 7.1 the average number of negative water node pressures are plotted against wind speed for five of the most devastating historical hurricane tracks. The synthetic tracks A1, B1, and C1 are also included to allow for comparison between the historical and synthetic tracks. By studying the historical tracks, it can be observed that the plotted curves of Hurricane Alice and Hurricane Lenny do not have the same nice shape as the other tracks. Also, at lower wind speeds (approximately below 80 knots), Alice and Lenny are more devastating than Georges, Irene, and Jose. As Alice and Lenny are further away from the island compared to the other tracks, also when studying the distance to the northern part of the island, these results does not fit with the above discussion about the correlation between the simulated damages and the track distance to the island. A possible explanation is that the hurricane movement direction of both Alice and Lenny differs from the reimaging hurricanes. Figure 7.2 presents a map of the hurricane tracks of Alice, Georges, Irene, Jose, and Lenny. While Georges, Irene, and Jose are moving in a northwestern direction, Alice moves towards southwest and Lenny towards southeast. The southern movement direction is perhaps more devastating at lower wind speed. But no conclusion can be made from these results, as such a hypothesis needs to be studied more closely with additional analyses and simulations.

Another explanation why there is no perfect correlation between the simulated damages and the estimated distances between the historical hurricane tracks and the island, is that the historical tracks are simulated with non-constant wind speeds values that variates up and down when the hurricanes travel over the ocean. The historical hurricanes had wind speeds that were either decreasing, increasing, or going both up and down as the hurricanes passed the area around St. Kitts, and these variations were included in the simulations. In comparison, the wind speeds

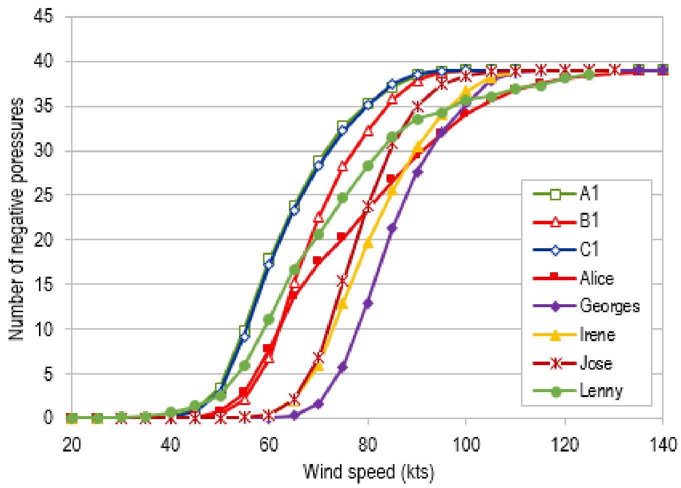


Figure 7.1: *Wind speed versus average number of negative water node pressures for some of the most devastating hurricanes tracks, namely A1, B1, C1, Alice, Georges, Irene, Jose, and Lenny.*

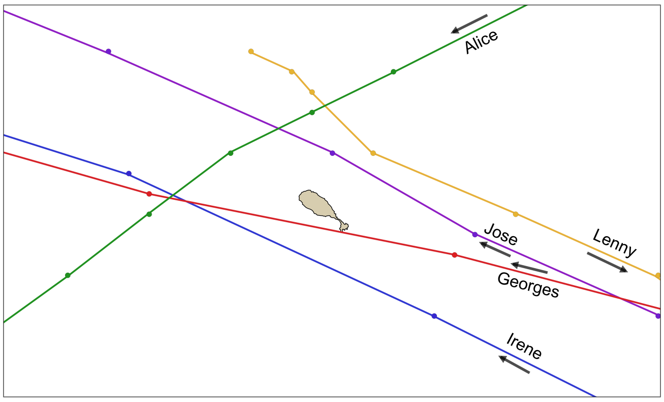


Figure 7.2: *Map of the historical hurricanes Alice, Georges, Irene, Jose, and Lenny. The arrows show which direction the hurricanes moved.*

of the synthetic tracks were constant. It is possible that the different variations in wind speed among the historical hurricanes affected the simulation results differently. By studying the wind speeds of the historical hurricanes presented in Figure 7.1 more closely, it was observed that while passing the area of St. Kitts the wind speed of Alice was more or less constant, the wind speed of Irene was increasing, and the wind speeds of Georges, Jose, and Lenny were all decreasing. No clear trend was found that could explain the results, and therefore, no conclusion regarding the effect of variations in wind speed can be made from these results.

7.4.3 Threatening hurricanes to St. Kitts

Among the simulated hurricanes in this case study, almost all hurricanes that passed the island within a radius of 46 km and had a wind speed above 100 knots at its closest track point resulted in a worst-case scenario regarding damages to the power system, i.e. the entire power system became non-functional. All these hurricanes resulted in the maximum potential of 39 negative pressures appearing in the water distribution system during the 72-hour simulations. Also, some hurricanes reached the maximum potential of 39 negative pressures at scenarios with wind speeds below 100 knots, and among these, the synthetic tracks A1 and C1 were the most devastating hurricane tracks, which it can be observed in Figure 7.1. Both tracks hit the island; C1 moving along the entire length of the island, and A1 crossing the island at the center close to the northern parts.

The factors that make hurricanes threatening to St. Kitts are that they either have a very high wind speed and are passing not too far away from the island, or they have a lower wind speed and are hitting the island. Hurricanes passing on the northern side of the island are also more threatening than hurricanes with the same distance to the island that are passing in the southern side, because the they are closer to the vulnerable parts of the power system, i.e. the Northern powerline.

7.5 Suggestions for infrastructure upgrades and preventative measures

The analyses performed in this case study have identified vulnerabilities in the power and water distribution system. This information enables the power and water distribution operators on St. Kitts to know which parts of the system that potentially could benefit the most from upgrades. Since the results found that the most vulnerable parts of the power system were the Northern powerline and the part of the Southern powerline located in the main city of Basseterre, a suggestion for an upgrade to the power system could be to replace the power poles along these areas with poles that have a stronger material that can withstand external stresses better. A suggestion to reduce the potential damages to the water distribution caused by power outages is to reduce the dependency between the systems. This can be done by for instance invest in stand-by power generators that can supply the wells with power in case of power outage. The result of the analyses found that the best place to install a stand-by generator is in the parish of St. Anne at the site of the power pole that supplies well 13 with power. Other good locations for installing stand-by generators are next to any of the wells along the western coast including the parishes of Trinity, St. Thomas, and St. Anne, and next to well 4 in the parish of St. Paul. Other suggestions to avoid damages to the distribution system in the case of power outage includes upgrading the piping network by replacing the pipes with pipes that can withstand large pressure drops better, and to install more storage tanks that can supply the system with water. The results found that the inlet of water from reservoir sources and storage tanks was lowest in the western and northern parts during power outages. Therefore, additional storage tanks should be installed in these areas.

But even if upgrades are yet to be made, preventative measures can be implemented prior to bad weather to reduce the damages to the power and distribution systems. The operators of the power system can mobilize a team for the northern areas of the island in order to reduce the repair time of the power system in case of damage. From the results of the analyses, it was shown that the potential damages to the distribution system can be significantly reduced by repairing the power system within a short time. If all the repair teams of the power system are located in and around Basseterre during bad weather, they risk using an unnecessarily long time to repair damages to the power systems that occurs in the north as the storm may have caused reduced accessibility on the roads. A suggestion for a preventative measure for the operators of the water distribution system is to shut down the system, if possible, during bad weather to prevent the pressure to drop inside the pipes in case of power outage. Such preventative measures can help minimize the recovery time and allow citizens to get access to electricity and water quicker in the time after the storm. Also, the cost of repairing damages can be reduced.

8 Conclusions

The objective of this thesis, which contributes to and extend the work by Brunner et al. (n.d.), was to present a case study of a risk analysis using a real-world interdependent infrastructure system, and thereby show that it is possible to perform such an analysis with limited amount of data. This was done by performing analyses of the power and water distribution systems on St. Kitts by utilizing simulation models built by Brunner et al. (n.d.), where the damages to the power system were caused by hurricanes passing by the island, and the effects on the distribution system were a result of non-functional water wells that had lost the electrical power supply. In the analyses performed in this thesis, synthetic hurricanes were used. The information and data about the infrastructure systems required to run the models were gathered from publicly available sources. The objective of the thesis is met as the performed analyses, both by Brunner et al. (n.d.) and in this thesis, have provided information that is valuable from a risk management perspective.

This information includes the following conclusions. The Northern powerline is the most vulnerable part of the power system, as this powerline supplies the highest number of wells with electrical power. A central part of the Southern powerline was also found to be vulnerable when the power outages lasted for multiple days. This central part of the powerline supplied some of the wells in the main city of Basseterre, which is the highest populated area on the island with the highest water demand. Beside the water supply from wells, water is supplied to the distribution system from storage tanks and reservoir sources. This supply from tanks and reservoirs was observed to become less adequate as the duration of the power outages increased, which means that St. Kitts is dependent on its water supply from wells to meet the water demand over time. When the linkages between the power system and the water distribution system were analyzed by removing the dependency on electrical power for one well at the time, the results showed that the most critical wells were the wells located on the western side of the island, closely followed by most of the wells in and around the main city of Basseterre. This finding was explained by the low concentration of storage tanks on the western side of the island, and that the eastern side of the island had higher inflow of water from reservoir sources.

In a risk management process, this information can be used to plan for upgrades to the power and water distribution system as well as for better implementation of preventative measures. Suggestions of upgrades to the systems included strengthening the vulnerable parts of the power system by replacing the power poles with poles that better withstand external stresses, strengthening the water distribution system by replacing pipes with stronger pipes that withstand pressures drops better, installing stand-by generators to supply the most critical wells in case of power outages, and installing more storage tanks in the areas with the most insufficient water inflow from tanks and reservoir sources in cases where power outages affected the entire power system. Suggestions of preventative measures that could be implementer prior to storms included mobilizing repair teams for the vulnerable parts of the power system, i.e. to the northern areas, to ensure quicker repair time of potential failures to the power system, and shutting down the water distribution system, if possible, to prevent large pressure drops to occur in case of power outages. The hurricane simulations identified which hurricanes that have the potential to cause the worst damages to the power system. These results can help the operators of the power and water distribution systems to know when to implement these preventative measures.

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