PUERTO RICO GRID RESILIENCE ASSESSMENT USING BINOMIAL ANALYSIS FOLLOWING HURRICANE MARIA CONSIDERING STORM EFFECTS

By

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ABSTRACT

YENKI NG. Puerto Rico grid resilience assessment using binomial analysis following
hurricane Maria considering storm effects
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Hurricane Maria was proven to be a very devastating storm in recent history. Ranked as the third costliest storm in the United States, Maria accumulated up to $90 billion in damages and accounted for at least 3,000 deaths. These deaths were primarily due to the aftermath of the storm for which it knocked out Puerto Rico's entire power grid, leaving 3.4 million people without electricity. The residents were struggling to survive with the lack of proper food and water supplies, health care, and contact services. It took approximately a whole year for the island to have complete power restoration, which was a major issue. Solutions to prevent, or, minimize such major power loss again are important for a small island like Puerto Rico. Various techniques of increased grid resiliency may be implemented, provided with a proper analysis. In this study, binomial analyses were completed to analyze the effects of different storm events that occurred as a result of hurricane Maria. The impact of each storm event along each region of the island were used to help determine adequate solutions to further improve the existing power grid. It is recommended to replace the existing the single-point support and two-legged transmission towers with four-legged towers. In addition, it is also recommended to replace rectangular pole structures with tubular pole structures. The suggested solutions will be immediate solutions; however, a long-term solution is suggested in relation to future intense storms. Complete details of such solutions are further explained in this report.

ACKNOWLEDGEMENTS

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Any opinions, findings, and conclusions expressed in this thesis are those of the authors and do not necessarily, reflect the views of the NSF or PREPA.

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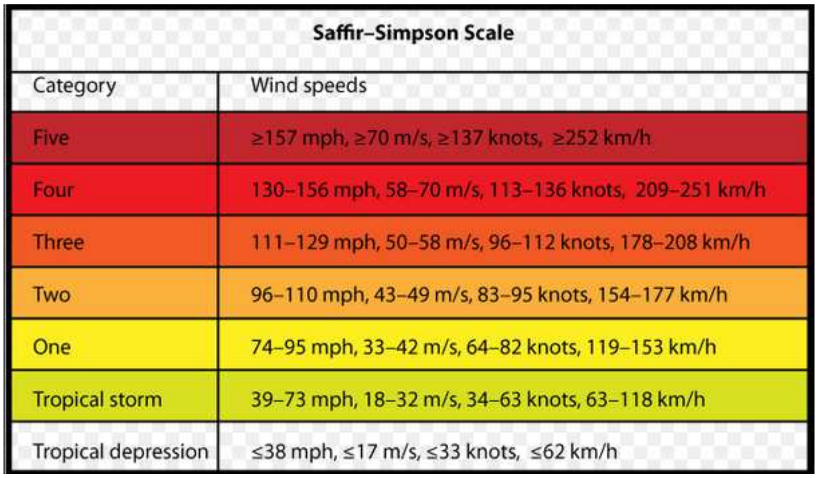
LIST OF ABBREVIATIONS

cm	Centimeters
ECA	Event Correlation Assurance
GHG	Greenhouse Gas
HLD	High Landslide Density
km/h	Kilometers per Hour
LLD	Low Landslide Density
m	Meters
PREPA	Puerto Rico Electric Power Authority

CHAPTER 1: INTRODUCTION

The 2017 hurricane season was proven to be a very active one for it produced seventeen named storms, ten of which became hurricanes. Six of these hurricanes were considered to be major storms based on the Saffir-Simpson scale (Categories 3-5), as shown in Figure 1.1. The result of the hurricane season was a devastating one, causing record-breaking damages. It was reported that the cumulative cost of 16 separate billion-dollar weather events in the United States, which includes weather events throughout the whole year, totaled to $306.2 billion in 2017 (NOAA, 2019). This shattered the previous record cost of $214.8 billion back in 2005 (NOAA, 2019). Majority of the cumulative cost was accumulated by three distinct hurricanes: Harvey, Irma, and Maria. These three hurricanes cost a total of $265 billion, with each costing about $125 billion, $50 billion, and $90 billion respectively (NOAA, 2019). The cost of each storm ranked them among the top five costliest U.S. hurricanes ever recorded. Although it was not the most economically damaging, hurricane Maria was one of the worst natural disaster on record.



Saffir–Simpson Scale

Category	Wind speeds
Five	≥157 mph, ≥70 m/s, ≥137 knots, ≥252 km/h
Four	130–156 mph, 58–70 m/s, 113–136 knots, 209–251 km/h
Three	111–129 mph, 50–58 m/s, 96–112 knots, 178–208 km/h
Two	96–110 mph, 43–49 m/s, 83–95 knots, 154–177 km/h
One	74–95 mph, 33–42 m/s, 64–82 knots, 119–153 km/h
Tropical storm	39–73 mph, 18–32 m/s, 34–63 knots, 63–118 km/h
Tropical depression	≤38 mph, ≤17 m/s, ≤33 knots, ≤62 km/h

Figure 1.1: Saffir-Simpson scale indicating storm intensity by wind speed.

Hurricane Maria peaked as a category 5 hurricane, topping at maximum wind speed of 278 km/h (Pasch et al., 2019). The storm traveled along the Caribbean Sea, hitting some of the islands along the northeastern portion. The two most noticeable locations devastated by the natural disaster were the islands of Dominica and Puerto Rico. Maria passed both the islands and their entireties, causing significant damages and deaths. It was initially reported that only 64 lives were lost as a result of the hurricane; however, that drastically changed to about 3,000 deaths, 11 months after the storm (Barajas, 2019). Most of these deaths were not necessarily due to the direct impact of Maria, but rather the aftermath. Maria destroyed 80% of Puerto Rico's utility poles and all transmission lines. This resulted in a complete power loss throughout the entire island. The 3.4 million people that resided in Puerto Rico at the time of the storm were essentially without any electricity for months. This caused complete loss of water supplies and cell phone services (Pasch et al., 2019). It was reported that only half the of the island's power was restored by the end of 2017, and 65 percent was restored by the end of January 2018 (Pasch et al., 2019). It took approximately a whole year for complete power restoration (Campbell, 2018).

The primary objective of this report is to determine the various storm scenarios and the severity of damages to infrastructures along the island of Puerto Rico following hurricane Maria. In using the damage scenarios, adequate solutions can be suggested to either prevent or minimize the damages to transmission structures so that a complete power loss should not occur again during future extreme storms. The objective will be supported by field and satellite data collected using both graphical and numerical analysis.

1.1 Hurricane Maria's Travel Path

Hurricane Maria, the storm originated off the west coast of Africa as a tropical wave back on September 12, 2017 (NOAA, 2019). As Maria made its way northwest towards the islands in the Caribbean Sea, southeast of the United States, it strengthened into a tropical storm on September 16th. Maria quickly intensified into a hurricane with wind speed at about 185 km/h the following day and became a category 5 hurricane just 12 hours later. On September 19th, Maria made its initial landfall on the island of Dominica. By that time, the hurricane was sustaining maximum winds of about 269 km/h with minimum central pressure of 92 kPa. After Dominica, Maria continued its same travel path and made way towards the island of Puerto Rico. Before reaching Puerto Rico, the hurricane peaked at a wind intensity of 278 km/h with a central pressure of 91 kPa. At the point of contact, in the southeast coast of the island, the maximum wind intensity weakened to about 250 km/h, just below the threshold of a category 5 hurricane. Hurricane Maria made its way through Puerto Rico from the southeast to the northwest with a duration of about several hours. After passing through Puerto Rico, the hurricane weakened again to about 176 km/h wind intensity. Maria kept its consistent travel path moving northwest until it changed its direction northward on September 22. While still maintaining a hurricane intensity, Maria traveled north for about 5 days. By September 27, Maria changed its course direction again, having now moved northeast until dissipation on October 2, 2017. Figure 1.2 shows the visual image of the travel path.

Tropical storms achieve maximum intensities if the maximum wind speed coincides with minimal air pressure (Peraza et al. 2014). If storm made landfall at its maximum intensity, then the most damaging effect may occur. Figure 1.3 shows the storm's pressure and intensity throughout its duration.

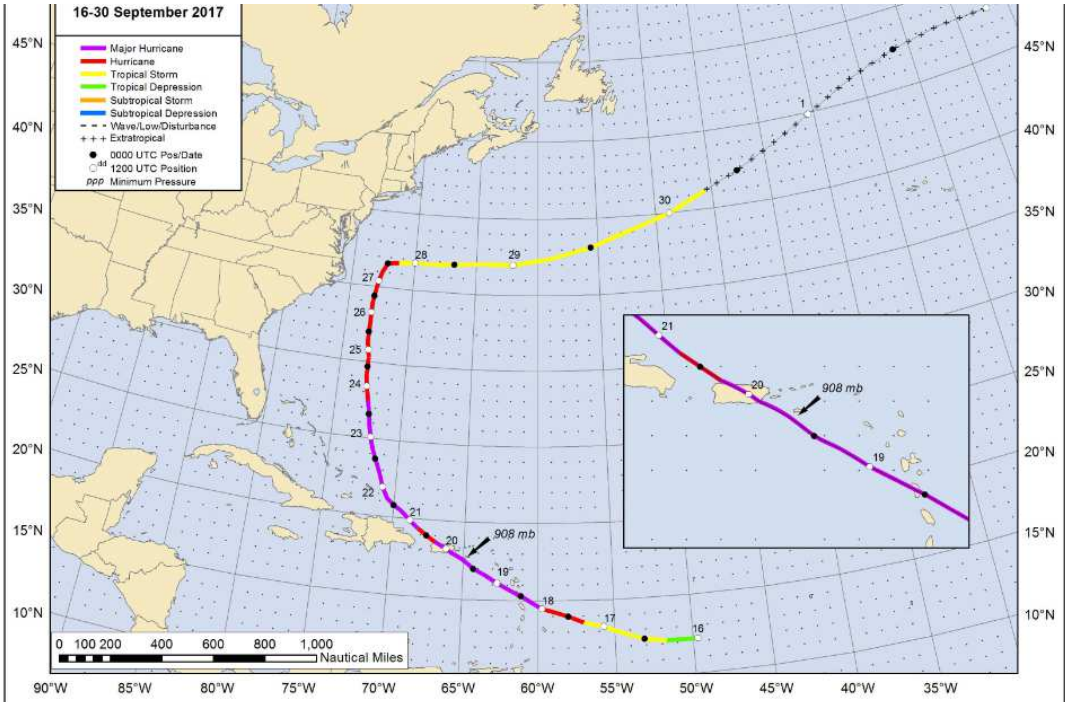


Figure 1.2: The visual representation of the travel path of Hurricane Maria (Pasch, et al., 2019).

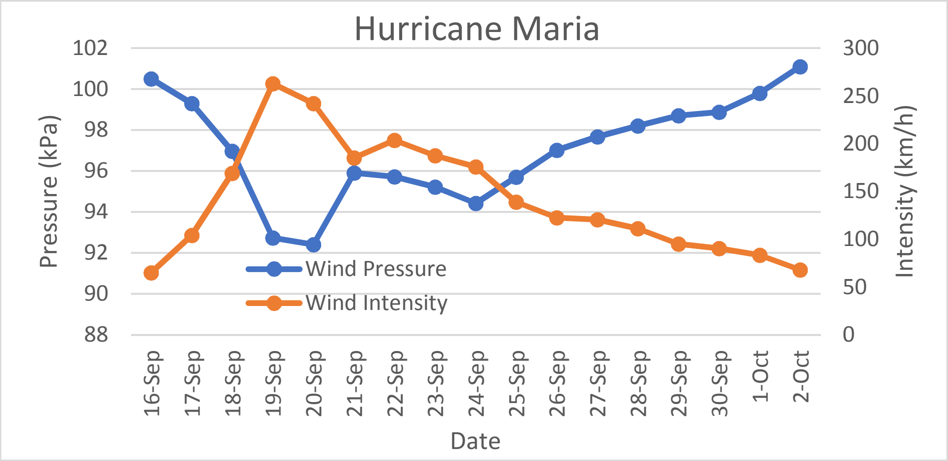


Figure 1.3**:** Hurricane Maria's average wind pressure and intensity by date (Pasch, et al., 2019).

1.2 Environmental Impact of Hurricane Maria

During and after the hurricane, Puerto Rico experienced various storm events as shown in Figure 1.4. In addition to the strong winds, storm events such as storm surge, rainfall and flooding, coastal and river erosion, deforestation, and landslides have occurred (Silva-Tulla et al. 2018). The topography of the island prior to the storm changed drastically following the storm, causing potential problems for the existing vegetation and wildlife. There were significant trees down due to the strong wind and torrential rain. These may be the causes of some or majority of the power grid to fail.

It was reported that Puerto Rico experienced a maximum inundation levels of 1.83 m to 2.74 m above ground level resulting from a combined effects of storm surge and tide (Pasch et al., 2019). Additional causes of such inundation levels can be attributed to heavy rainfalls, which was recorded at a peak of 96.5 cm. Figures 1.5 and 1.6 show the inundation and rainfall levels throughout the island during Maria. Such high levels of rainfall during the hurricane caused a major occurrence of landslides. According to Bessette Kirton et al. (2019), hurricane Maria triggered more than 40,000 landslides in at least three-fourths of Puerto Rico's 78 municipalities. This was caused by elevated pore-water pressure within the soil as a result of the heavy rainfall. It was recorded that the antecedent soil moisture in both LLD and HLD areas were 13% and 11% above average, respectively (Bessette-Kirton, et al., 2019).

Figure 1.4: Images of storm events captured following hurricane Maria (NSF Rapid, 2018).

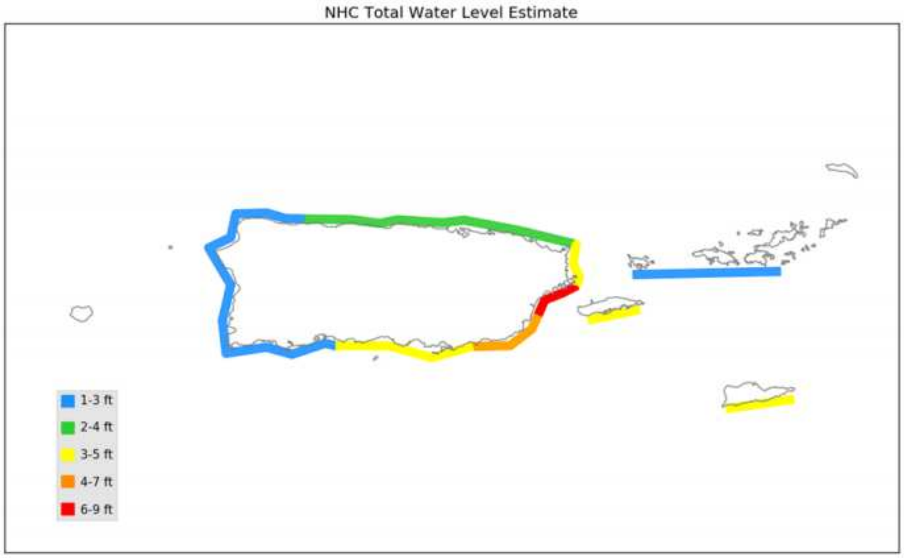


Figure 1.5: Inundation levels from storm surge in Puerto Rico (Pasch et al., 2019).

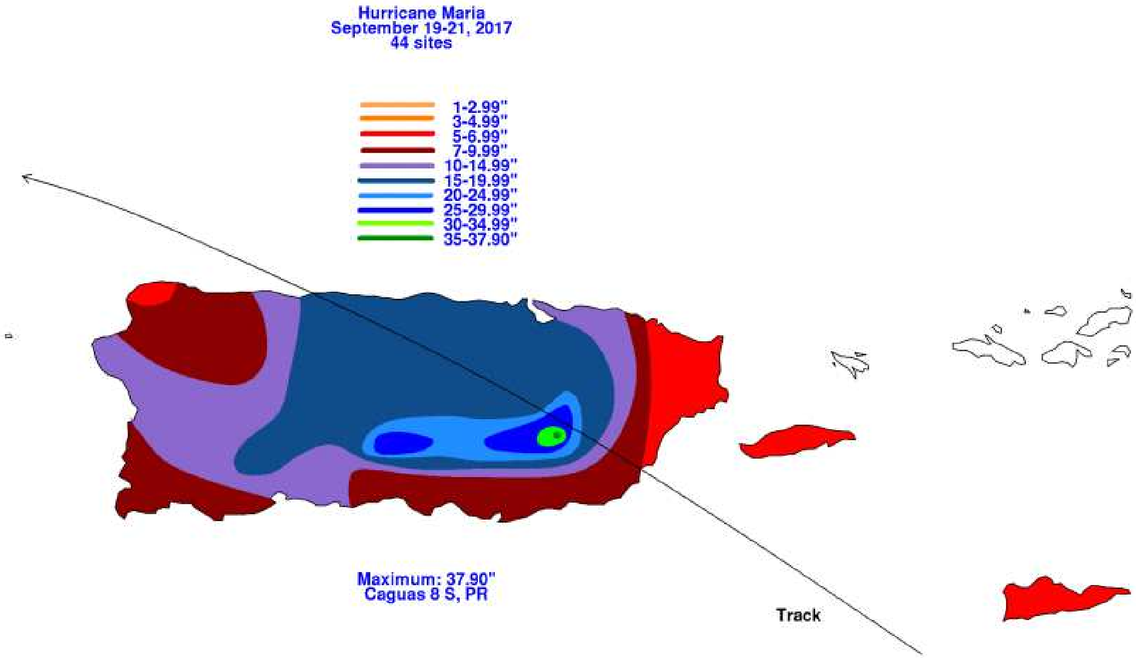


Figure 1.6: Rainfall levels throughout Puerto Rico (Pasch et al., 2019).

CHAPTER 2: PUERTO RICO'S POWER GRID

PREPA is one of the largest public power companies in the United States and the public corporation in charge of the electrical infrastructure of Puerto Rico, Vieques, and Culebra. PREPA's power grid of Puerto Rico is regionally divided into seven sections as shown in Figure 2.1. The electric system has more than 3,862 km of transmission lines (230 and 115 kV), 51 115-kV transmission centers, 283 substations (38 kV), and over 48,280 km of distribution lines (13.2, 8.32, 7.2, and 4.16 kV); the electric system configuration throughout the island is shown in Figure 2.2. The conventional, fossil fired, installed generation capacity of the Puerto Rico electric system is 5,839 MW with 3,443 MW of these installed in the south coast of the Island. These southern generators are also the least expensive energy producers; thus, although the installed capacity in the south represents 59% of the total capacity approximately 70% of the energy generated is produced in the south coast. Since 70% of the electricity demand occurs in the north coast, specifically in the northeast, resiliency of the transmission system becomes crucial to deliver the expected energy.

Figure 2.1: PREPA'S regional map.

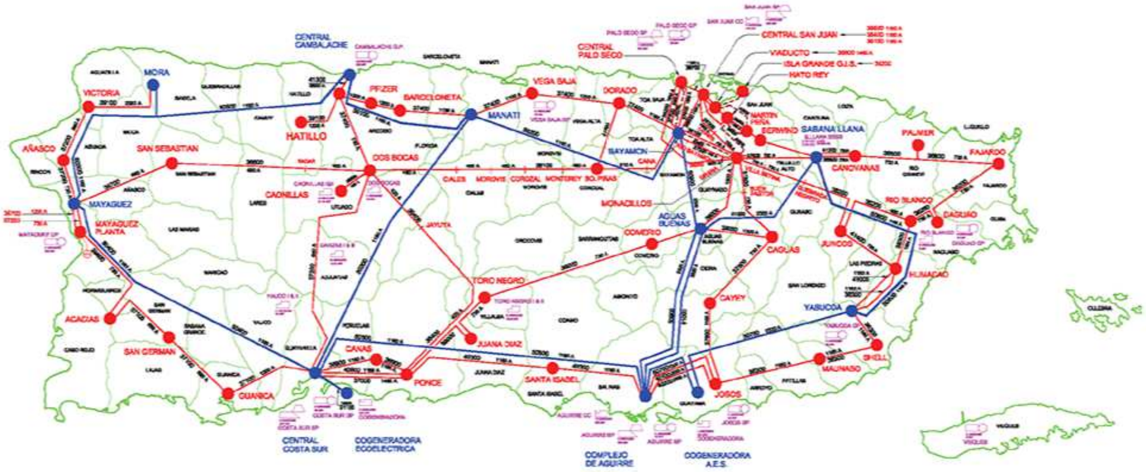


Figure 2.2: Puerto Rico’s power electric system configuration (PREPA, 2018).

Due to the constraints imposed by the central mountain range, the power structures are seen to spread out along the coastal areas with some very important high voltage lines run along the mountain ridges to connect the southern generation with northern demands. Support structure types for the power grid in Puerto Rico includes concrete and steel poles (common for low voltage power transmission and distribution) and large truss towers (common for the transmission of power at 230 kV and 115 kV). Truss structures include lattice structures, guyed trusses, H-frames, as well as single column delta structures. Wood poles are the predominant structure for power distribution lines.

2.1 Power Grid After Hurricane Maria

Entering from the southeastern corner of the island, hurricane Maria inflicted Puerto Rico’s power infrastructure with severe physical structure damages. Figure 2.3 shows several power pole structures damaged by buckling, conductors down, and loss of equipment such as insulators, communications or transformers on pole. The damage modes observed on the transmission poles also included foundation failures as a result of land movements (slides or debris flows).

Figure 2.3: Various modes of damages to transmission structures (PREPA, 2018).

The grid performance data is shown in Figure 2.4, where the region with the most significant power loss was actually on the east coastal area. Figure 2.4 is presented in a 5 km x 5 km grid format. Each grid represents the averaged effects within the cell based on the provided scale. The scale on the diagram has been normalized by the maximum effect. Damaged power systems throughout Puerto Rico were proven to be a substantial problem because the entire island had succumbed to complete power outage. According to Lluveras (2018), it took eleven months for the entire island to fully restore its electricity.

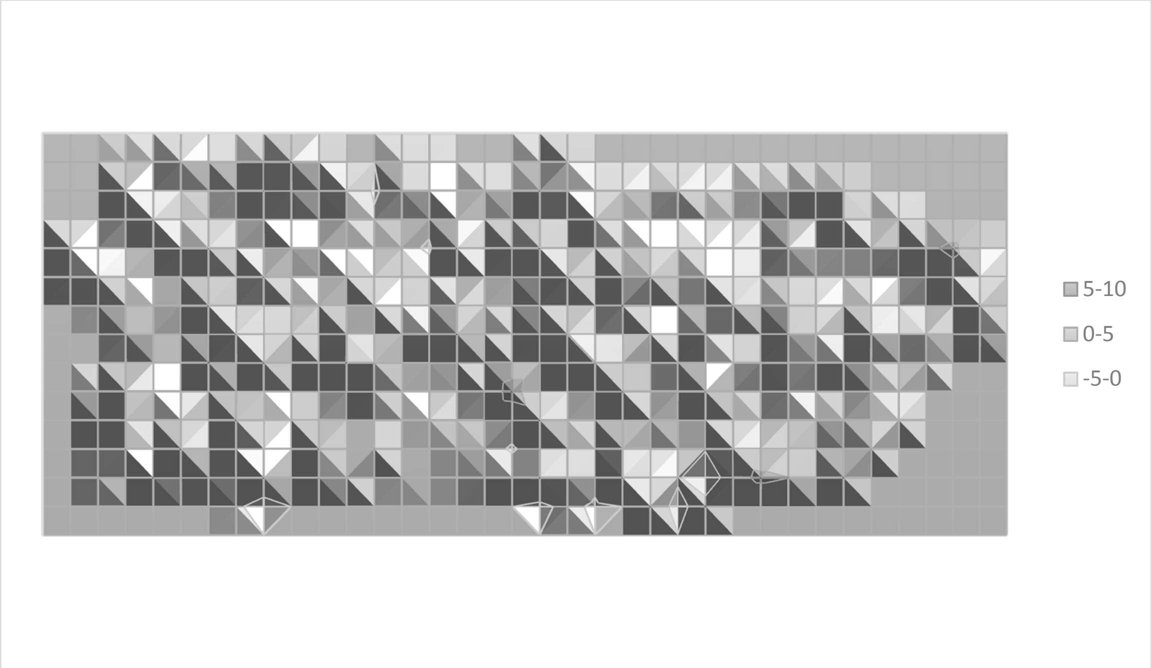


Figure 2.4: Impact of Maria on the power grid as determined by comparing the before and after night satellite image illuminance (normalized units).

2.2 Power Structural System Failure

Power structure failures during the strong storm event can lead to different electric faulting in the grid system from simple flickering, voltage swell and sag, to complete power outage. The power structure failure in Puerto Rico after Maria included significant number of downed powerlines, collapsed lattice towers, knocked down steel, concrete and wood poles, broken arms, broken insulators and jumpers, loose guy anchors and foundation failures. For example, a 115 kV line in Humacao has seen 14 structures experienced significant damages and seven lattice structures completely knocked down. Figure 2.5 shows several damage modes of failed utility structures during Maria. It is recognized that several of the guyed rigid Y transmission towers with single point supports have collapsed under high winds or heavy rain. The post-disaster reports did not differentiate the various modes of structural failure. Hence, it is not known if the structures failed after the guy lines lost tensions or the wind has brought the entire structure down. However, it can be presumed that each structure experienced the possible damages as follow: Structure A experienced tensile failure causing complete collapse, structure B failed at the base due to bending, torsional failure caused structure C to collapse, and structure D experienced buckling which caused the "Y-shaped" portion to separate from the entire structure.

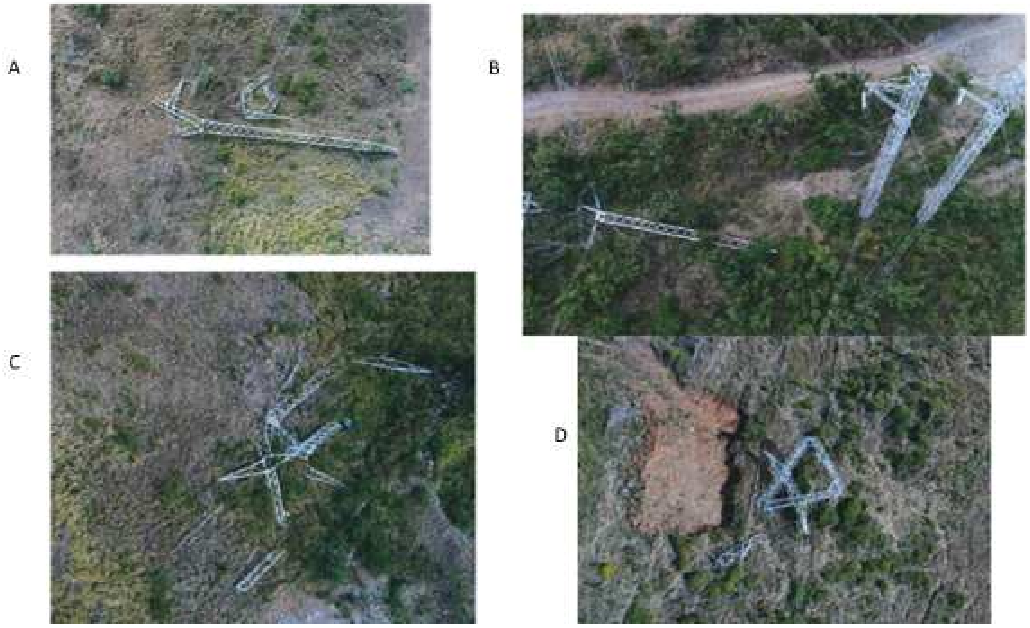


Figure 2.5: Various modes of damages of transmission structures (PREPA, 2018).

CHAPTER 3: RESEARCH METHODOLOGY

Following hurricane Maria, data was collected for structural assessment. The purpose of the structural assessment was to determine the damage severity of each individual infrastructure using a basic rating system. This technique provides a comprehensive appreciation of the damage extents. The rating system consists of defining a damaged infrastructure as either minor, moderate, or major; table 3.1 shows a description of each category. Sample sizes included a collection of both photographic and satellite images. Over 10,000 photographs and 7,000 satellite images were collected; however, these sample sizes were subjected to variance due to skewed data. After assessing the infrastructures damage severity, the collected samples were used for further storm analysis.

Table 3.1: Proposed rating system for structural assessment.

Category	**Description**	**Color Indicator**
Minor	Minimal damages and is still safe to be inhabitable	Green
Moderate	Extensive damages and must be proceeded with caution	Blue
Major	Substantial damages and uninhabitable. Proceed with extreme caution	Red

Both the photographic and satellite images serve different purposes for their respective analyses. The photographs were stored in a website database which features data from both hurricane Irma and Maria with the following link: https://cybergis.uncc.edu/hurricane/. The website was generated for public view to gain insight on the location on which these photos were captured and the significance of damages of each infrastructure. In addition, the website also provides brief descriptions and characteristics of the hurricanes. These photographs were captured by a field/research team that was sent to Puerto Rico in early May 2018, eight months after the storm. The team consisted of both civil and electrical engineers. Within a seven-day travel span, the team captured photographs throughout most of the island starting from the west coast and making its way to the east coast. These photographs include a various range of the island's existing condition such as topography, roadways, and different types of infrastructures (transmission, residential, commercial, etc.). Figure 3.1 below shows some example of images that were captured during the field study.

Figure 3.1: Images of structural damages captured during the field study (NSF Rapid, 2018).

Satellite images were collected using Google Earth^{TM} for further binomial analysis both graphically and numerically. The structural rating of each infrastructure was determined for the satellite images using the color indicator provided in Table 3.1. The ratings were used to develop two statistics: The overall damage severity along each region as defined in Figure 2.1 and an average overall rating for regions based on a 5 km x 5 km grid system (Figure 3.2) as shown in Appendix A with vector labeled as "Structures". The data collected from the satellite images consisted of primarily infrastructures such as commercial and residential buildings as shown in Figure 3.3. Once completed, a binomial analysis was used to correlate storm scenarios to damaged structures.

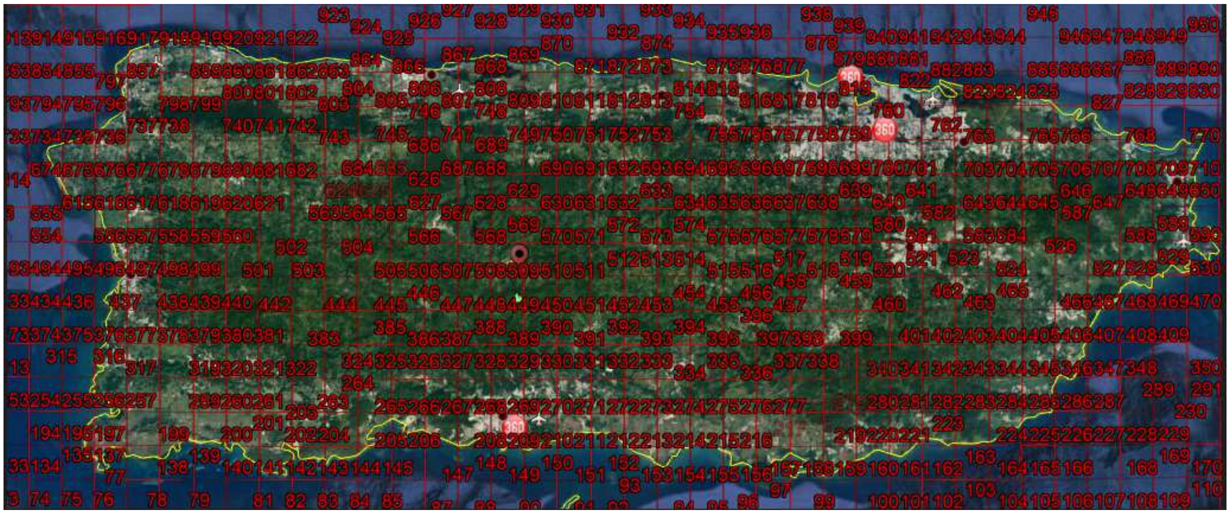


Figure 3.2: 2 km x 5 km grid overlay of Puerto Rico.

Figure 3.3: Complete structural assessment for Puerto Rico.

The binomial analysis consists the use of rating systems in both the structural assessment and storm scenarios. The purpose of this analysis was to develop a relationship corresponding to how much influence/impact a specific storm scenario had on the infrastructure damages along each region. This well help determine whether the damages in each region were caused by a single or multiple storm scenario. As stated previously, the outcomes of the analysis were presented both graphically and numerically. The intended purpose of these diagrams/graphs are to give visual representation of the intensity of various storm scenarios along Puerto Rico. To determine the correlation between two storm events (r and q), the storm effect analysis was performed using an Effect Correlation Assurance (ECA) factor, which is defined as:

$$\text{Effect Correlation Assurance } (ECA) = \frac{\left|\{\varphi_A\}_r{}^T\{\varphi_x\}_q\right|^2}{(\{\varphi_A\}_r{}^T\{\varphi_A\}_r)(\{\varphi_x\}_q{}^T\{\varphi_x\}_q)} \qquad \text{Eq. (1)}$$

where:

$$\{\varphi_A\}_r = Structural\ Assessment\ Vector\ \ r$$

$$\{\varphi_x\}_q = Storm\ Effect\ Vector\ q$$

$$\{\varphi_A\}_r{}^T = Transpose\ of\ \{\varphi_A\}_r$$

$$\{\varphi_x\}_q{}^T = Transpose\ of\ \{\varphi_x\}_q$$

The ECA was modeled after the development of the ordinary coherence calculation associated with computation of the frequency response functions (Pastor et al., 2012). It is a statistical indicator of the closeness of two vectors and is insensitive to small changes or small magnitudes. For the purpose of this analysis, it is used as a spatial correlation analysis to determine the relationship between storm event and structural damage, helping understand the amount of impact that each storm scenario had along each specific region. The ECA is developed into matrix format based on Figure 3.1. If the ECA value is represented as 1 along each entry, it is indication of the two vectors being identical in its respective spatial region. Otherwise, it indicates that they are not identical.

Following the ECA determination, average values of non-zero terms in each ECA arrays were determined. This singular value represents the closeness of the two matrices presented in each ECA array and will indicate how much of an impact the particular storm scenario had along the entire island. It is defined as:

$$I_x = \frac{\sum ECA_x}{n} \quad \text{Eq. (2)}$$

where I_x is the influence factor due to a specific storm event x, ECA_x is the values of non-zero entries, and n is the number of entries. The normalized ECA, $I_{x,}$ is a value between 0 and 1, where 0 represents no impact or influence due to the storm scenario and 1 represents a very strong impact on the power loss from the particular storm event. The following section discusses the results of the computation of the ECAs and I_x.

CHAPTER 4: RESULTS

Multiple results were determined based on the various analyses stated in Chapter 3. First, the storm effect data was generated into a 5 km x 5 km grid values that cover the entire island. Figures 4.1 and 4.2 show the graphical image of the various storm events based on the grid system of Figure 3.1. Figure 4.3 displays the damaged severity along each region defined by PREPA; this is supported by the data provided in Table 4.1. Figures 4.4-4.9 shows the ECA of various storm events in relation to structural damage. And Table 4.2 is the average influence factor of each storm event.

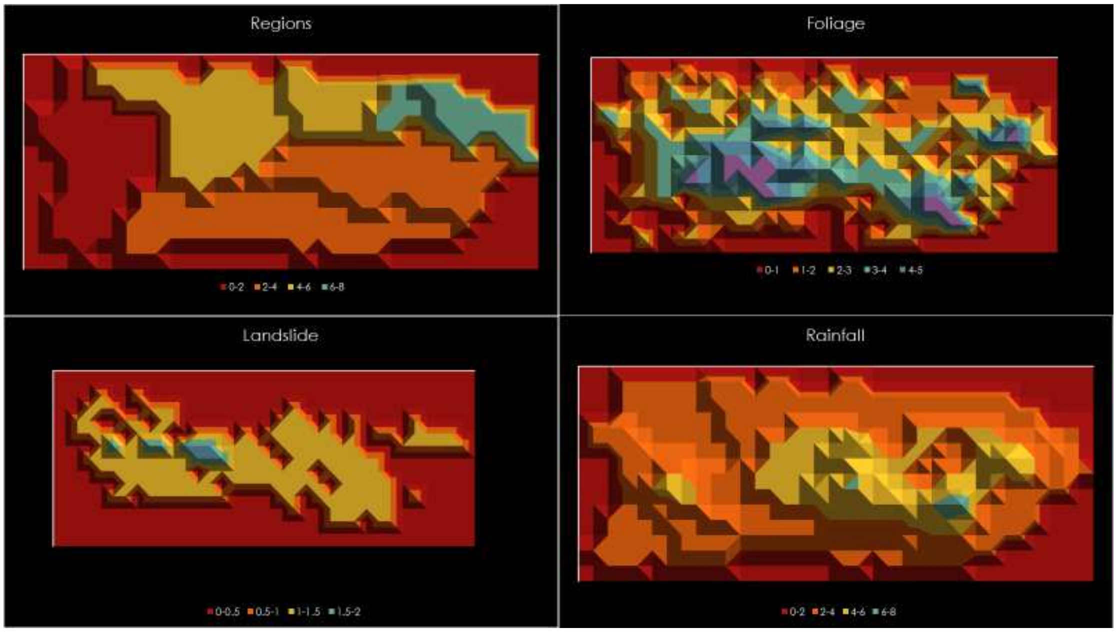


Figure 4.1: Graphical ratings of regions, foliage/deforestation, landslide, and rainfall.

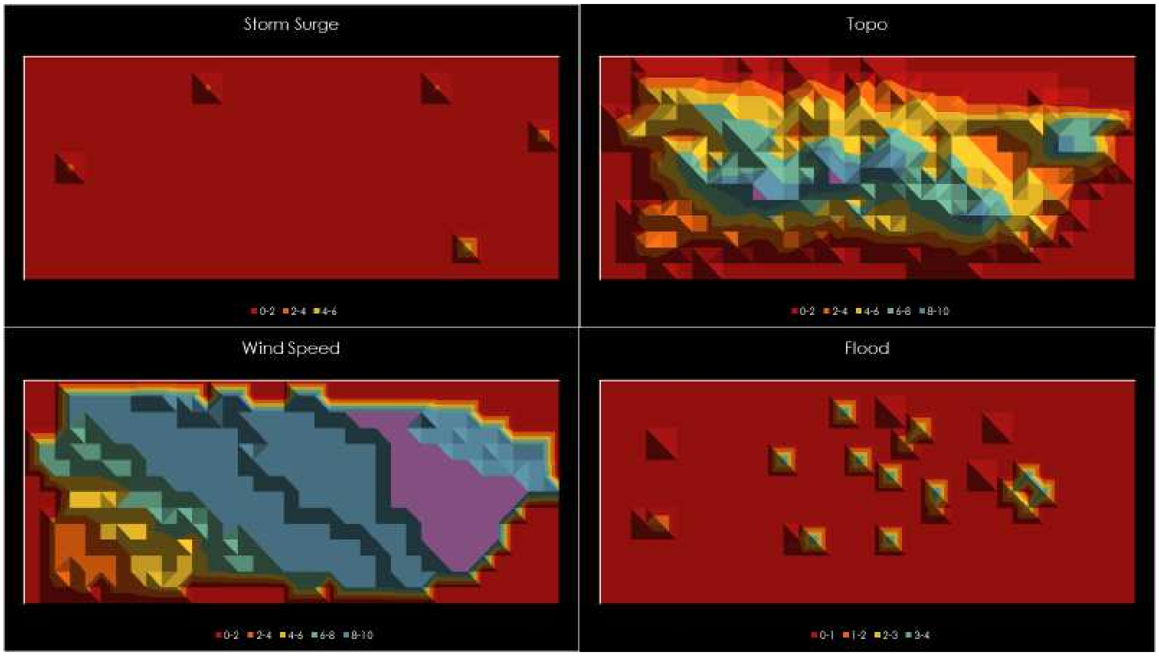


Figure 4.2: Graphical ratings of storm surge, topography, wind intensity, and flooding.

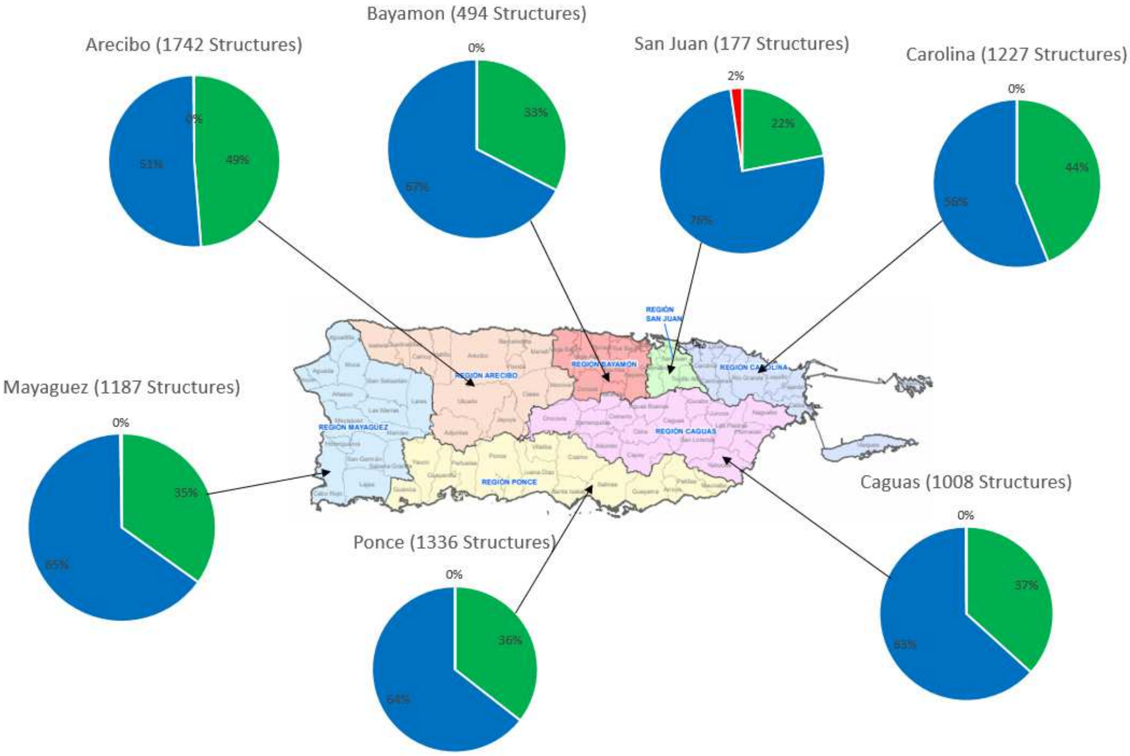


Figure 4.3.: Damage severity along each region of Puerto Rico.

Table 4.1: Quantitative values of damage severity.

PUERTO RICO STRUCTURAL ASSESSMENT			
	Damage Severtiy		
Region	**Minor**	**Moderate**	**Major**
Arecibo	849	891	2
Bayamon	161	333	0
San Juan	39	134	4
Carolina	539	688	0
Caguas	370	637	1
Ponce	475	861	0
Mayaguez	414	770	3
Total	2847	4314	7

As shown in Figures 4.1 and 4.2, the storm effects, including loss of foliage/deforestation/trees down, landslide and rainfall, showed varied damage severities that are also varied in spatial distributions. As a result, the individual contribution to the overall damages to structures and infrastructures will be different. It is desired that the computation of the ECAs and I_x can help reveal the levels of contribution by storm effect types.

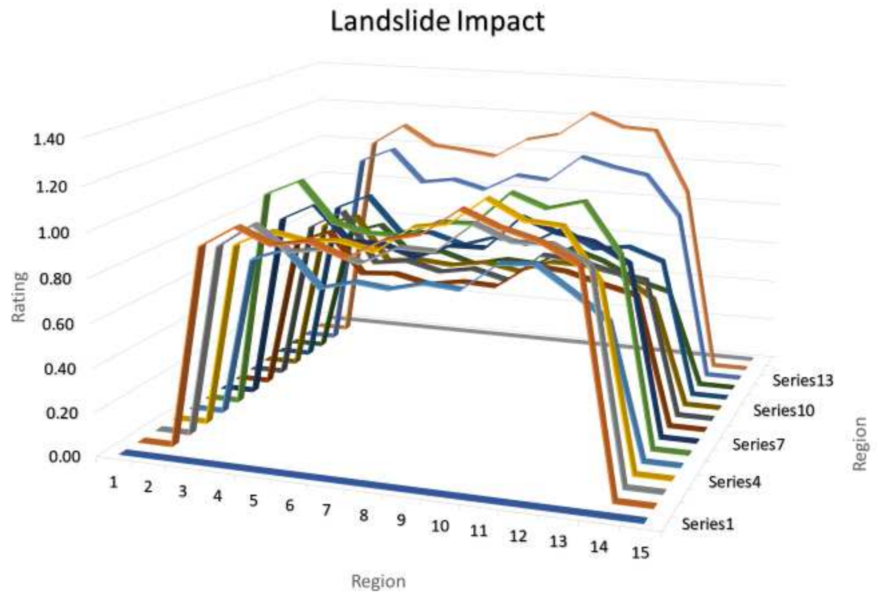


Figure 4.4: ECA for landslide impact.

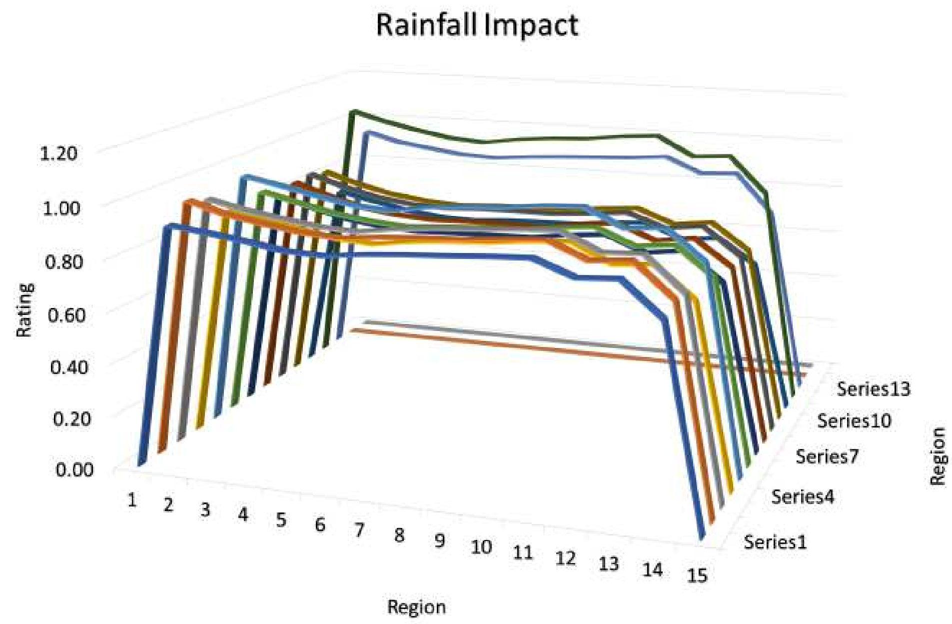


Figure 4.5: ECA for rainfall impact.

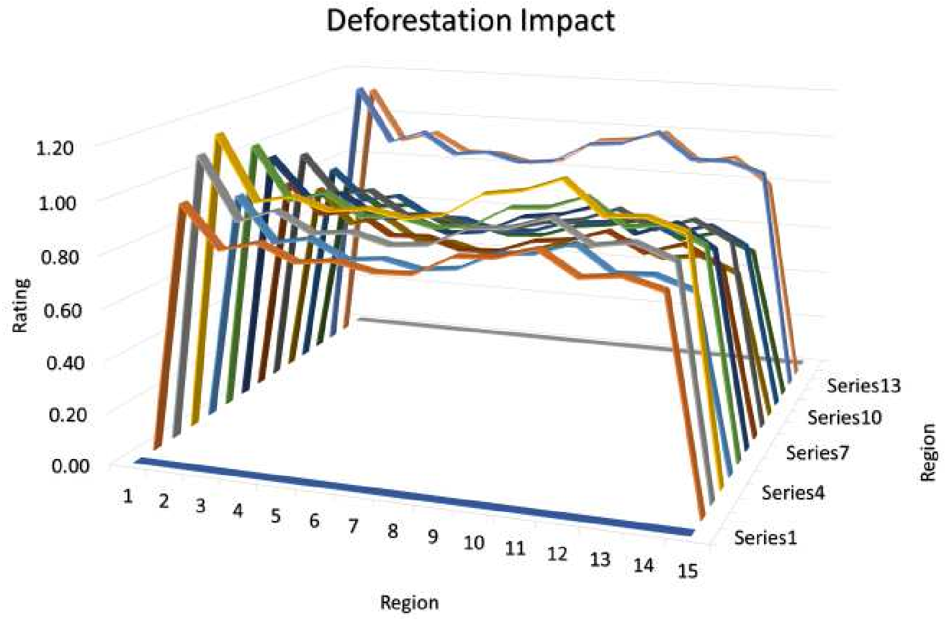


Figure 4.6: ECA for deforestation impact.

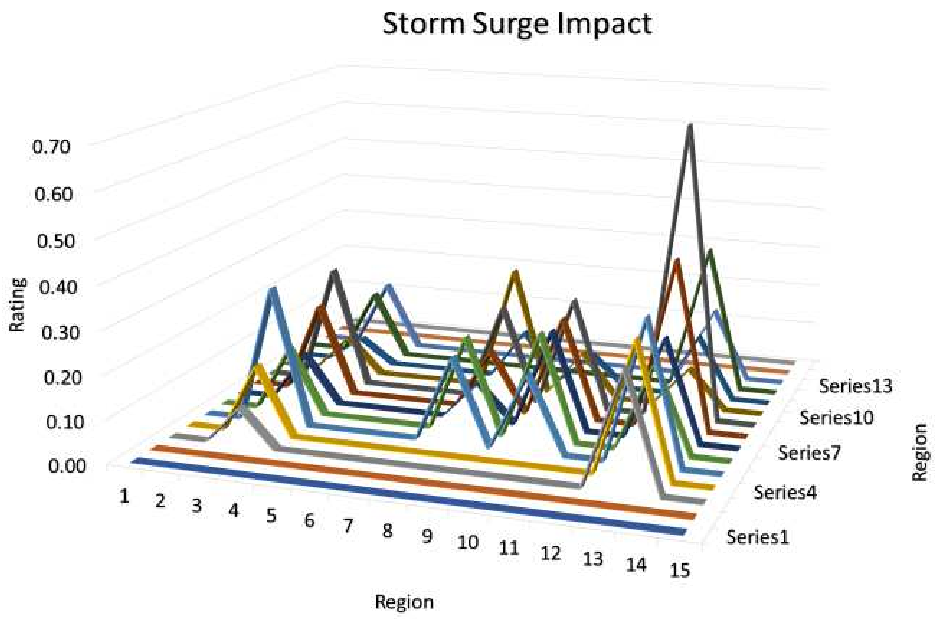


Figure 4.7: ECA for storm surge impact.

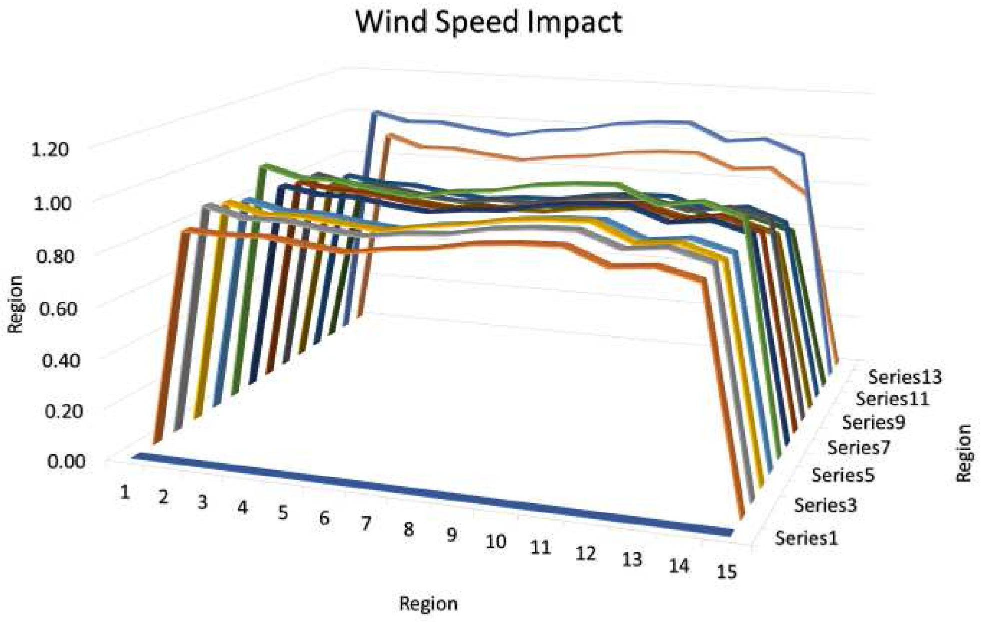


Figure 4.8: ECA for wind impact.

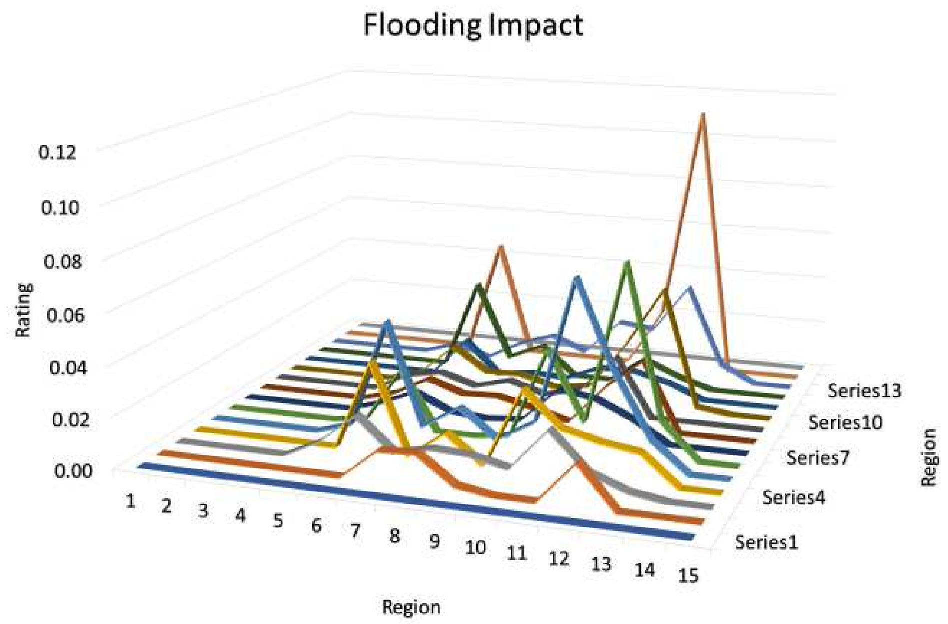


Figure 4.9: ECA for flooding impact.

Table 4.2 shows the Ix values for different storm events. Based on the results, it is observed that strong wind is the most significant factor contributing to the damaging effects of hurricane Maria. The second most significant storm effect is torrential rain. Together with landslides and deforestation, these storm effects rounded up the four top effects with each having an I_x value above 0.8. Storm surge and flooding are the least storm effects.

Table 4.2: Average value of each ECA arrays.

Influence Factor	
Storm Event	**I_x**
Landslide	0.82
Rainfall	0.86
Deforestation	0.81
Storm Surge	0.21
Wind	0.85
Flooding	0.02

CHAPTER 5: DISCUSSION

Throughout Puerto Rico, there were significant amounts of infrastructure damages observed through the field study and data collection. These damages were influenced by many possible storm effects as indicated in the results in Chapter 4. As shown in Figure 4.3, majority of the structures were moderately damaged than minor damages in each region. Overall, out of 7168 structures analyzed, 39.7%, 60.2%, and 0.1% were at a damage severity of minor, moderate, and major, respectively. The six storm effects that were considered may dictate the type of damages that have occurred at each individual structure. However, the rating technique is not sensitive enough to reflect on the damage effects. More detailed structural evaluations need to be performed to discern specific failure mores (Peraza et al. 2014).

5.1 Correlation of Results

Based on the data of Figures 4.1 and 4.2, various conclusions can be made: First of all, deforestation occurred predominantly throughout the entire island with the exception of the coastlines. This is reasonable because of the elevated landscape makes the vegetation more receptive to the damaging effects of strong wind. The central portion along the Arecibo and Ponce region, the southeast, and northeast had the highest deforestation rating. Landslides also occurred throughout the entire island with a strong focus at the central portion, wherein Mayaguez and Arecibo regions have the highest landslide rating. Heavy rainfall was experienced throughout the entire island with most of the rainfall intensity occurring along the central area within the Caguas region. There were minimal occurrences of storm surge and flooding, most of which were along the northern and central region of Puerto Rico. And finally, extremely high wind intensity was experienced throughout the entire island with the exception of the southwest portion in Mayaguez region. Figures 4.4 through 4.9 are the numerical analyses that support these conclusions.

In evaluating the ECA data (Appendix A and Figures 4.4-4.9), validation of the data can be confirmed for the correlation of storm events to structural damages. Storm events such as wind intensity, landslide, rainfall, and deforestation display that the most of the values along each figure are approaching 1, indicating that the two vectors are nearly identical. However, the figures for storm surge and flooding indicate that the vectors are not identical since most of the data does not approach 1. To verify that these observations are true, the influence factor, I_x, for each storm event was determined.

The ECA data developed were used to indicate the influence factors shown in Table 4.1 and they are ranked from highest to lowest as follow: rainfall, wind intensity, landslide, deforestation, storm surge, and flooding. As previously stated, the first four storm events indicated in the ratings have influence factor of at least 0.8. This indicates that the majority of structural damages were caused by these events. Storm surge and flooding had influence factors below 0.25, with the implication of causing only minimal damages to structures studied.

The above structural damage causation analysis was then applied (storm effect analysis) to the damaged states of the transmission line structures. It is assumed that the transmission lines and structures damaged were directly impacted by the same storm effects and damage data from PREPA were used to validate the information collected from this study.

5.2 Grid Resiliency of Puerto Rico's electric system

With observations determined through the correlation of storm events in relation to damaged structures, possible solutions can be generated to help the decision-making process for grid hardening strategies that can eliminate future occurrence of another complete blackout in Puerto Rico. In other words, the outcomes of current study can be used to improve grid resiliency of the electrical power system. Resiliency is more than just lessening the likelihood of such occurrences; it is also about limiting the scope and impact of such occurrences, restoring power rapidly afterwards, and learning from these experiences to better deal with events in the future (NAP, 2017). Since 80 percent of the island's utility poles were destroyed and all of the transmission lines were knocked out, finding techniques to help mitigate that is imperative. A strong recommendation will be the use of grid hardening techniques such as replacing the existing transmission and pole structures with structures that can withstand high-intense loading from the multiple forces of a natural disaster like a hurricane. However, these are dependent on the damaging causes of each individual damaged structure.

It is observed that several downed structures are guyed, single point support structures with failure modes including total structure collapses, structural member buckling and torsion failures. To minimize failures of transmission towers (as shown in Figure 2.5), it is recommended to replace those structures with four-legged transmission structures as shown in Figure 5.1. Single point supported structures lack lateral stability, especially closer towards the foundation, to withstand extreme wind conditions. It can result in many modes of failure such as bending, torsion, buckling, large deflection, etc. In using a four-legged tower structure, it creates a more stable condition towards the foundation, reducing the amount of potential swaying compared to that of a single point structure. Compared to a three-legged transmission tower, the four legged-tower was proven to be 20% more economical and has deflected 38.25% less (Panchal et al, 2016). Thus, making this a potential option for implementation.

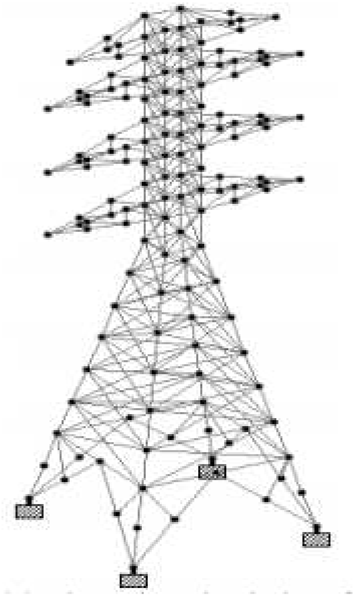


Figure 5.1: Three-dimensional view of the four-legged tower (Kumar et al., 2016).

Another possible solution for extreme weather conditions are the use of round/tubular pole structures. These types of structures are advantageous to withstanding intense wind and rainfall because of its smaller wind profile and flexible rigidity compared to that of rectangular structures. Tubular structures also are less likely to have torsional effects and can allow for more tip deflection than rectangular structures. It is precautious, however, to implement these in areas where there are likely occurrences of storm events such as flooding, storm surge, and landslide because of the lack of foundation stability.

Both solutions can be adequate for similar storm events in the future provided that they are properly incorporated in specific regions where they can be effective. It is recommended to replace single point structure with four-legged structure within areas that is likely to experience all of the critical intense storm effects and replace pole structures with tubular shapes in areas in which flooding, storm surge, and landslide is likely happening.

5.3 Future Intense Weather Concerns

The biggest concern moving forward is the likely occurrence of another massive storm that can possibly cause the same impact as hurricane Maria. This cause for concern is the result of climate change. Recent analyses concluded that there are possible decreases in the frequency of tropical storm occurrences; however, the frequency of categories 4 and 5 hurricanes have a projected increase to 45-87 percent ("Hurricanes and Climate Change," 2019). Figure 5.2 below shows a trend line of hurricane occurrences dating back to 1851 in the Atlantic. Climate change can attribute to such increase in hurricane intensity because of warmer sea surface temperatures and the rise of sea level.

Hurricanes can form with the four following conditions: a pre-existing weather disturbance such as a tropical wave, warm water of at least 26.5 degrees Celsius over a depth of 50 m, thunderstorm activity, and low wind shear (USDOC, 2013). Climate change can be attributed to both natural and human causes as shown in Figure 5.3 (EPA, 2016). It can be indicated from the trendline in Figure 5.3 that human factors are causing a rapid rate of increase in the global temperature. The primary reason is the constant use of fossil fuel resulting in the increase emissions of greenhouse gases (GHG), which can absorb solar energy and release it into the atmosphere; therefore, increase the global temperature.

With potential increase occurrences of storm events as intense as hurricane Maria, it is also recommended to also find solutions for reducing carbon emission or GHG increase. Understanding climate change will be just as important as preventing massive power loss in order to prepare for future storms.

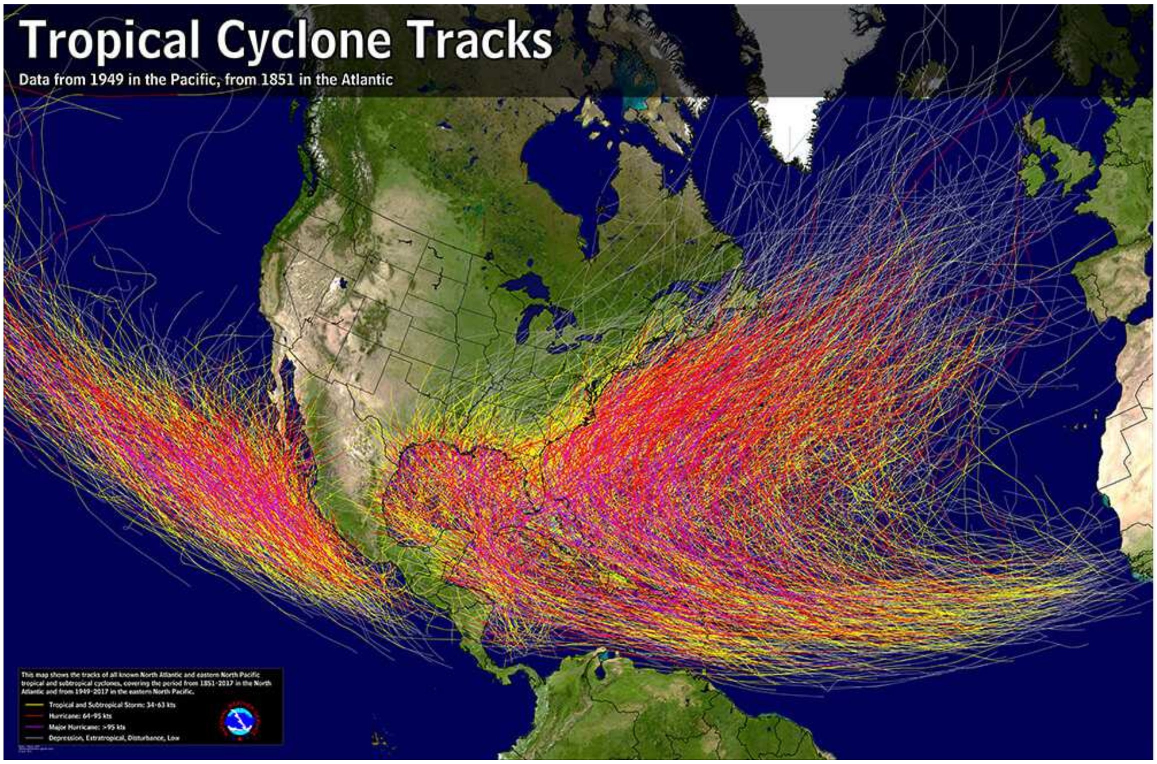


Figure 5.2: Trendline of hurricane occurrences (C2ES, 2019).

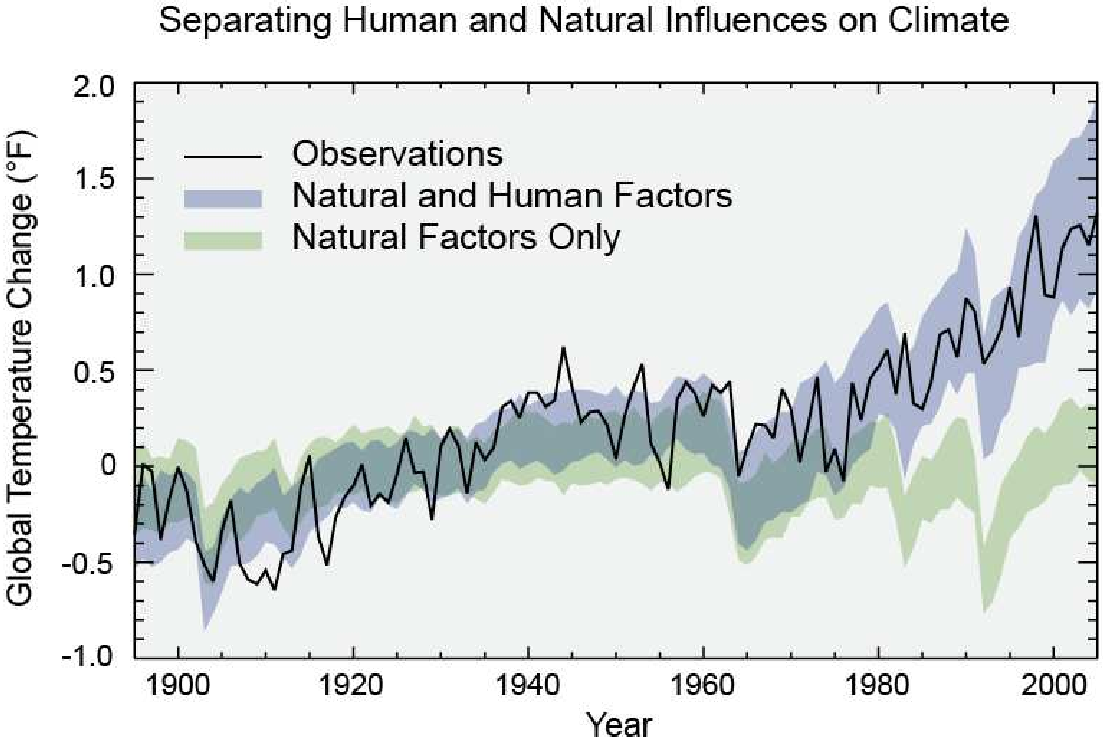


Figure 5.3: Trendline of the factors of temperature increase (EPA, 2016).

CHAPTER 6: SUMMARY AND CONCLUSIONS

This thesis presents the results of a reconnaissance mission to Puerto Rico that was funded by NSF (Rapid Project) to assess damage of electrical power grid in Puerto Rico due to the 2017 hurricane Maria. The thesis summarized the main observations of this Rapid mission and describes the resilience assessment study performed using a binomial study. The goal of this study is to determine possible solutions for the hardening of the transmission structures against future storms. As stated previously, all of Puerto Rico's power supply was destroyed leaving the island without power for nearly a year. From this research, the following conclusions were established:

- From the collected images of structural damaged, majority of them were considered moderately damaged.
- The above observation does not include failed infrastructures such as failed bridges, dams and roadways.
- A binomial analysis that determines the ECA factors has been performed, which helped establish the correlations of individual storm effect to the power grid failure scenario after Maria. The ECA factors are then used to compute the I_x values.
- The structural damage assessment and I_x computation concluded that rainfall, landslides, deforestation, and wind intensity had strongest correlations to infrastructure damages as oppose to storm surge and flooding, which have much lower correlations. Hence,
- There were high levels of structural damages due to rainfall, landslides, deforestation, and wind intensity during hurricane Maria. There were minimal effects from storm surges and flooding.

- It is recommended to use four-legged transmission towers and tubular pole structures where necessary and permissible.

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APPENDIX A: ECA CALCULATIONS

A.1. ECA Vectors

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0 & 0 & 0 & 0 & 3 & 3 & 3 & 4 & 4 & 3 & 3 & 3 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 3 & 3 & 3 & 3 & 2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 3 & 3 & 3 & 2 & 2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

$$ss := \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.56 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.4 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2.35 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 5.44 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 3.17 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

$$Wind := \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 6 & 6 & 0 & 0 & 0 & 0 \\
0 & 2 & 3 & 3 & 3 & 3 & 0 & 0 & 6 & 6 & 6 & 0 & 0 & 0 & 0 \\
0 & 2 & 2 & 3 & 3 & 3 & 5 & 4 & 6 & 6 & 7 & 8 & 8 & 8 & 0 \\
0 & 3 & 3 & 3 & 3 & 3 & 5 & 4 & 6 & 7 & 7 & 7 & 8 & 8 & 0 \\
0 & 0 & 3 & 3 & 4 & 4 & 5 & 4 & 6 & 7 & 7 & 8 & 8 & 8 & 0 \\
0 & 3 & 3 & 3 & 4 & 4 & 6 & 4 & 7 & 7 & 8 & 8 & 8 & 8 & 0 \\
0 & 3 & 4 & 4 & 5 & 4 & 6 & 6 & 7 & 7 & 8 & 8 & 8 & 8 & 0 \\
0 & 4 & 4 & 4 & 5 & 4 & 6 & 6 & 8 & 8 & 8 & 8 & 8 & 9 & 0 \\
0 & 5 & 4 & 4 & 5 & 7 & 6 & 6 & 8 & 8 & 8 & 8 & 8 & 9 & 0 \\
0 & 5 & 5 & 5 & 6 & 7 & 7 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 0 \\
0 & 0 & 5 & 5 & 4 & 8 & 7 & 8 & 8 & 8 & 8 & 8 & 9 & 8 & 0 \\
0 & 0 & 6 & 6 & 7 & 7 & 8 & 8 & 8 & 8 & 8 & 8 & 10 & 0 & 0 \\
0 & 0 & 6 & 7 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 9 & 10 & 0 \\
0 & 0 & 7 & 7 & 7 & 8 & 8 & 8 & 8 & 8 & 8 & 8 & 9 & 10 & 0 \\
0 & 0 & 7 & 7 & 8 & 8 & 8 & 8 & 8 & 9 & 8 & 9 & 9 & 0 & 0 \\
0 & 0 & 7 & 8 & 8 & 8 & 8 & 8 & 9 & 9 & 9 & 9 & 9 & 0 & 0 \\
0 & 0 & 8 & 8 & 8 & 8 & 8 & 8 & 9 & 9 & 9 & 9 & 9 & 0 & 0 \\
0 & 7 & 8 & 8 & 8 & 8 & 9 & 9 & 9 & 9 & 9 & 9 & 9 & 10 & 0 \\
0 & 7 & 8 & 8 & 8 & 8 & 9 & 9 & 9 & 9 & 9 & 9 & 9 & 10 & 0 \\
0 & 0 & 8 & 8 & 8 & 8 & 9 & 9 & 9 & 9 & 9 & 9 & 10 & 0 & 0 \\
0 & 8 & 8 & 8 & 8 & 9 & 9 & 9 & 9 & 9 & 9 & 9 & 10 & 0 & 0 \\
0 & 8 & 8 & 8 & 8 & 9 & 9 & 9 & 9 & 9 & 9 & 10 & 10 & 0 & 0 \\
0 & 8 & 8 & 8 & 9 & 9 & 9 & 9 & 9 & 9 & 9 & 10 & 10 & 0 & 0 \\
0 & 8 & 9 & 9 & 9 & 9 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 0 & 0 \\
0 & 9 & 9 & 9 & 9 & 9 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 0 & 0 \\
0 & 9 & 9 & 9 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 9 & 10 & 0 & 0 \\
0 & 0 & 9 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 9 & 8 & 0 & 0 \\
0 & 0 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 9 & 9 & 8 & 0 & 0 \\
0 & 0 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 10 & 9 & 8 & 8 & 0 & 0 \\
0 & 0 & 0 & 10 & 10 & 10 & 10 & 10 & 10 & 9 & 9 & 8 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 10 & 10 & 10 & 10 & 10 & 9 & 8 & 8 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 10 & 10 & 10 & 8 & 8 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 10 & 9 & 8 & 8 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 9 & 8 & 8 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

$$\mathrm{Structures} := \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 2 & 0 & 0 & 0 & 0 \\
0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 & 1 & 2 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 2 & 2 & 2 & 2 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 2 & 0 \\
0 & 0 & 2 & 0 & 0 & 0 & 2 & 1 & 2 & 0 & 2 & 2 & 0 & 2 & 0 \\
0 & 0 & 2 & 1 & 0 & 0 & 2 & 0 & 1 & 2 & 2 & 0 & 0 & 0 & 0 \\
0 & 2 & 2 & 2 & 2 & 1 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 1 & 0 \\
0 & 2 & 2 & 2 & 0 & 1 & 2 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 0 & 2 & 2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 \\
0 & 0 & 2 & 2 & 0 & 0 & 2 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 \\
0 & 0 & 1 & 2 & 2 & 2 & 2 & 0 & 1 & 0 & 0 & 0 & 2 & 0 & 0 \\
0 & 0 & 2 & 0 & 0 & 2 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 2 & 2 & 2 & 0 & 0 \\
0 & 0 & 0 & 2 & 2 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 2 & 2 & 0 & 2 & 0 & 0 \\
0 & 0 & 2 & 2 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 2 & 2 & 0 \\
0 & 0 & 2 & 0 & 2 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 2 & 0 & 0 \\
0 & 0 & 2 & 0 & 2 & 0 & 2 & 2 & 2 & 2 & 1 & 0 & 2 & 0 & 0 \\
0 & 0 & 0 & 0 & 2 & 2 & 0 & 2 & 0 & 2 & 0 & 0 & 2 & 3 & 0 \\
0 & 2 & 1 & 0 & 2 & 0 & 0 & 2 & 0 & 2 & 0 & 2 & 2 & 0 & 0 \\
0 & 2 & 2 & 0 & 0 & 2 & 2 & 2 & 0 & 0 & 2 & 2 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 2 & 2 & 2 & 0 & 0 & 2 & 0 & 2 & 0 & 0 \\
0 & 1 & 2 & 0 & 0 & 2 & 0 & 0 & 2 & 0 & 2 & 0 & 1 & 0 & 0 \\
0 & 2 & 2 & 2 & 0 & 0 & 2 & 2 & 0 & 0 & 2 & 2 & 2 & 0 & 0 \\
0 & 0 & 2 & 0 & 0 & 0 & 2 & 2 & 2 & 0 & 3 & 0 & 1 & 0 & 0 \\
0 & 0 & 2 & 0 & 0 & 0 & 2 & 2 & 2 & 0 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 2 & 2 & 2 & 0 & 0 & 2 & 2 & 0 & 0 & 2 & 2 & 0 & 0 \\
0 & 0 & 0 & 0 & 2 & 0 & 2 & 0 & 0 & 0 & 1 & 2 & 2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 0 & 2 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 0 & 0 & 2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 2 & 1 & 2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

A.2. ECA Calculations

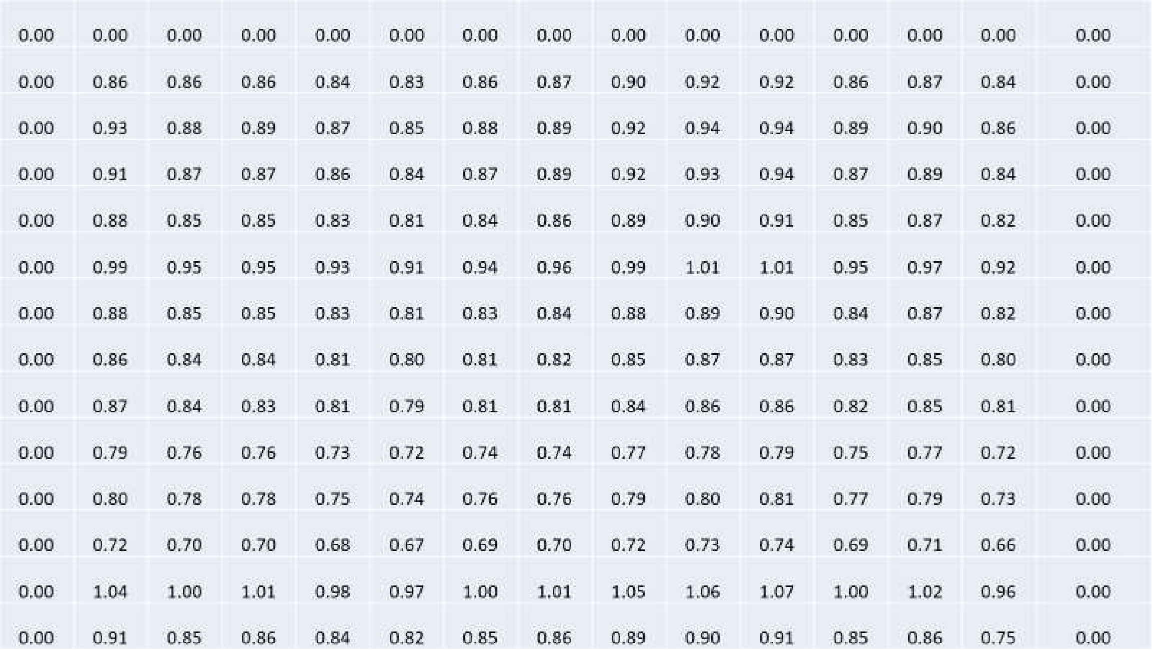
$$ECA_{Deforestation} = \frac{\left|\{\varphi_A\}_{Structures}{}^{T}\{\varphi_x\}_{Forest}\right|^2}{(\{\varphi_A\}_{Structures}{}^{T}\{\varphi_A\}_{Structures})(\{\varphi_x\}_{Forest}{}^{T}\{\varphi_x\}_{Forest})} =$$

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.97	0.80	0.84	0.78	0.80	0.77	0.78	0.85	0.86	0.91	0.82	0.84	0.80	0.00
0.00	1.12	0.88	0.93	0.86	0.87	0.84	0.85	0.92	0.94	0.99	0.90	0.92	0.86	0.00
0.00	1.18	0.92	0.95	0.91	0.93	0.91	0.93	1.02	1.04	1.09	0.97	0.98	0.93	0.00
0.00	0.91	0.73	0.76	0.69	0.70	0.68	0.69	0.76	0.77	0.83	0.72	0.73	0.68	0.00
0.00	1.08	0.87	0.91	0.83	0.84	0.81	0.82	0.91	0.92	0.97	0.87	0.89	0.82	0.00
0.00	1.01	0.86	0.88	0.80	0.80	0.75	0.77	0.84	0.86	0.91	0.81	0.86	0.77	0.00
0.00	0.87	0.75	0.77	0.69	0.69	0.65	0.66	0.71	0.73	0.77	0.70	0.75	0.67	0.00
0.00	0.97	0.80	0.83	0.74	0.75	0.70	0.71	0.75	0.78	0.83	0.76	0.81	0.74	0.00
0.00	0.79	0.65	0.69	0.60	0.60	0.57	0.58	0.63	0.63	0.67	0.61	0.63	0.57	0.00
0.00	0.85	0.72	0.75	0.67	0.67	0.63	0.64	0.69	0.70	0.74	0.68	0.73	0.65	0.00
0.00	0.75	0.67	0.68	0.61	0.62	0.58	0.59	0.64	0.66	0.70	0.62	0.66	0.59	0.00
0.00	1.16	0.93	0.98	0.89	0.91	0.87	0.89	0.97	0.98	1.04	0.93	0.94	0.89	0.00
0.00	1.13	0.91	0.95	0.88	0.88	0.84	0.87	0.96	0.98	1.01	0.90	0.93	0.82	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

$$ECA_{Rainfall} = \frac{\left|\{\varphi_A\}_{Structures}{}^{T}\{\varphi_x\}_{rf}\right|^2}{(\{\varphi_A\}_{Structures}{}^{T}\{\varphi_A\}_{Structures})(\{\varphi_x\}_{rf}{}^{T}\{\varphi_x\}_{rf})} =$$

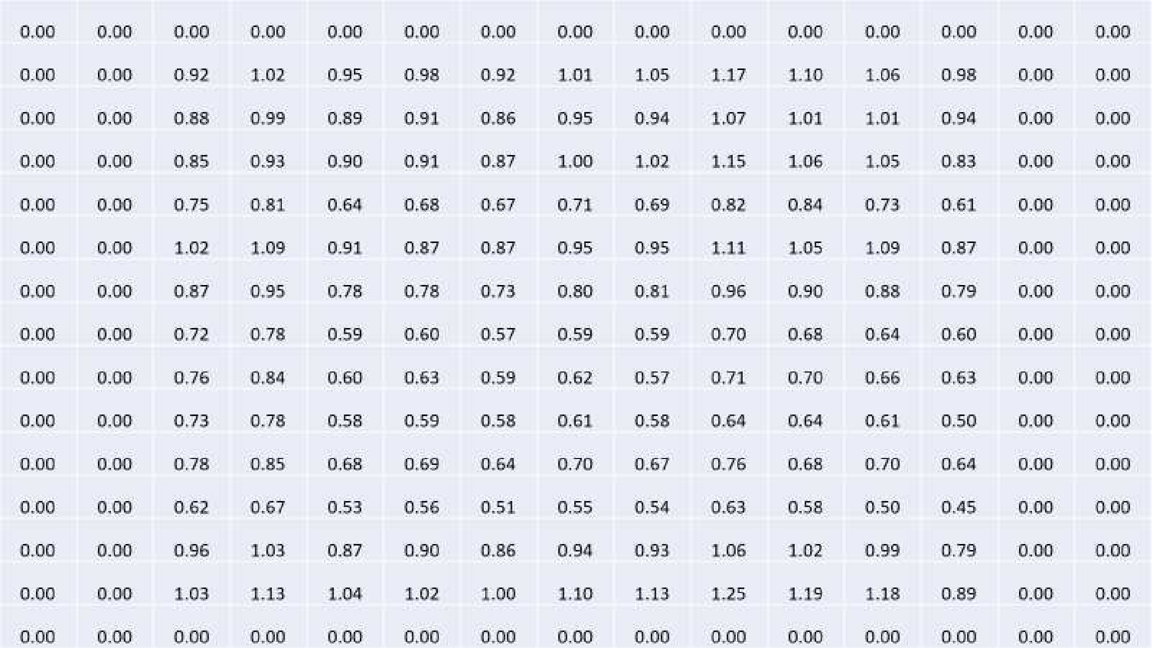
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.93	0.92	0.90	0.88	0.87	0.89	0.90	0.91	0.92	0.92	0.87	0.88	0.75	0.00
0.00	1.00	0.95	0.93	0.91	0.90	0.92	0.92	0.93	0.94	0.95	0.89	0.91	0.78	0.00
0.00	0.97	0.94	0.92	0.90	0.89	0.91	0.93	0.94	0.95	0.95	0.89	0.90	0.76	0.00
0.00	0.90	0.87	0.84	0.82	0.81	0.83	0.85	0.85	0.87	0.88	0.81	0.82	0.70	0.00
0.00	1.00	0.98	0.95	0.92	0.91	0.93	0.95	0.95	0.97	0.98	0.91	0.92	0.81	0.00
0.00	0.91	0.88	0.85	0.83	0.82	0.83	0.83	0.84	0.86	0.87	0.81	0.83	0.71	0.00
0.00	0.86	0.83	0.79	0.77	0.76	0.77	0.77	0.78	0.80	0.81	0.75	0.77	0.66	0.00
0.00	0.89	0.85	0.81	0.79	0.78	0.78	0.79	0.79	0.81	0.82	0.77	0.79	0.68	0.00
0.00	0.90	0.86	0.82	0.80	0.80	0.81	0.81	0.81	0.82	0.84	0.78	0.80	0.69	0.00
0.00	0.88	0.84	0.81	0.79	0.78	0.79	0.79	0.79	0.81	0.82	0.77	0.79	0.68	0.00
0.00	0.77	0.74	0.71	0.69	0.68	0.69	0.70	0.70	0.72	0.73	0.67	0.69	0.59	0.00
0.00	1.10	1.06	1.03	1.01	1.00	1.02	1.03	1.04	1.06	1.07	0.99	1.00	0.86	0.00
0.00	0.98	0.95	0.93	0.91	0.90	0.92	0.93	0.93	0.94	0.95	0.89	0.90	0.74	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

$$ECA_{Wind} = \frac{\left|\{\varphi_A\}_{Structures}{}^{T}\{\varphi_x\}_{Wind}\right|^2}{(\{\varphi_A\}_{Structures}{}^{T}\{\varphi_A\}_{Structures})(\{\varphi_x\}_{Wind}{}^{T}\{\varphi_x\}_{Wind})} =$$



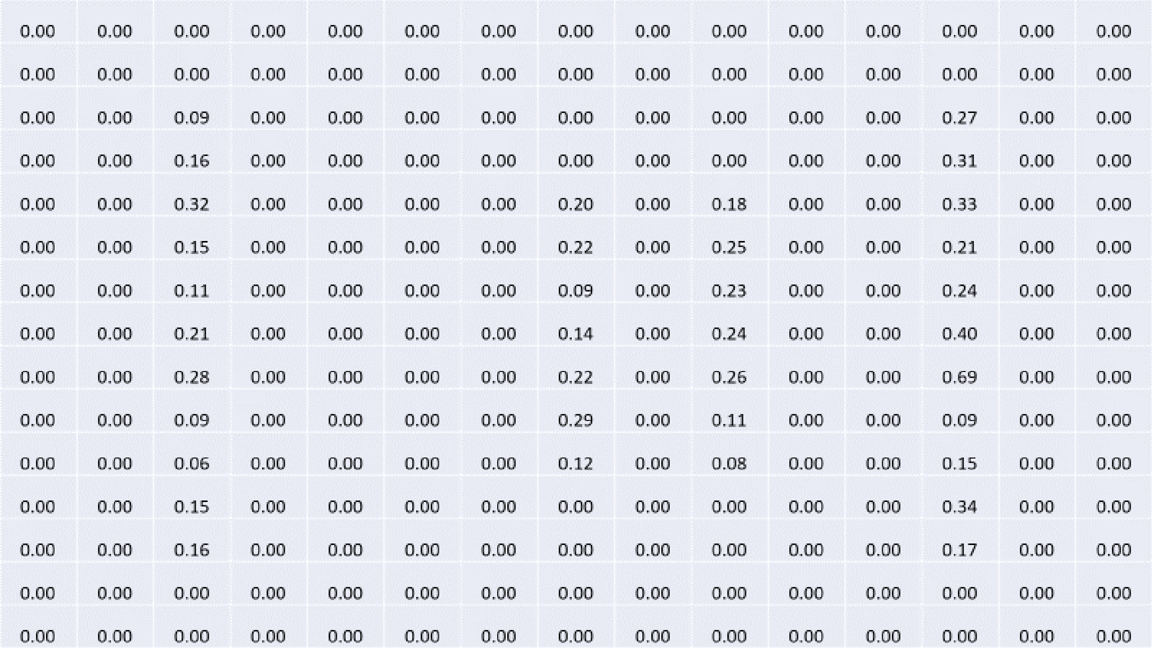
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.86	0.86	0.86	0.84	0.83	0.86	0.87	0.90	0.92	0.92	0.86	0.87	0.84	0.00
0.00	0.93	0.88	0.89	0.87	0.85	0.88	0.89	0.92	0.94	0.94	0.89	0.90	0.86	0.00
0.00	0.91	0.87	0.87	0.86	0.84	0.87	0.89	0.92	0.93	0.94	0.87	0.89	0.84	0.00
0.00	0.88	0.85	0.85	0.83	0.81	0.84	0.86	0.89	0.90	0.91	0.85	0.87	0.82	0.00
0.00	0.99	0.95	0.95	0.93	0.91	0.94	0.96	0.99	1.01	1.01	0.95	0.97	0.92	0.00
0.00	0.88	0.85	0.85	0.83	0.81	0.83	0.84	0.88	0.89	0.90	0.84	0.87	0.82	0.00
0.00	0.86	0.84	0.84	0.81	0.80	0.81	0.82	0.85	0.87	0.87	0.83	0.85	0.80	0.00
0.00	0.87	0.84	0.83	0.81	0.79	0.81	0.81	0.84	0.86	0.86	0.82	0.85	0.81	0.00
0.00	0.79	0.76	0.76	0.73	0.72	0.74	0.74	0.77	0.78	0.79	0.75	0.77	0.72	0.00
0.00	0.80	0.78	0.78	0.75	0.74	0.76	0.76	0.79	0.80	0.81	0.77	0.79	0.73	0.00
0.00	0.72	0.70	0.70	0.68	0.67	0.69	0.70	0.72	0.73	0.74	0.69	0.71	0.66	0.00
0.00	1.04	1.00	1.01	0.98	0.97	1.00	1.01	1.05	1.06	1.07	1.00	1.02	0.96	0.00
0.00	0.91	0.85	0.86	0.84	0.82	0.85	0.86	0.89	0.90	0.91	0.85	0.86	0.75	0.00

$$ECA_{Landslide} = \frac{\left|\{\varphi_A\}_{Structures}{}^{T}\{\varphi_x\}_{ls}\right|^2}{(\{\varphi_A\}_{Structures}{}^{T}\{\varphi_A\}_{Structures})(\{\varphi_x\}_{ls}{}^{T}\{\varphi_x\}_{ls})} =$$



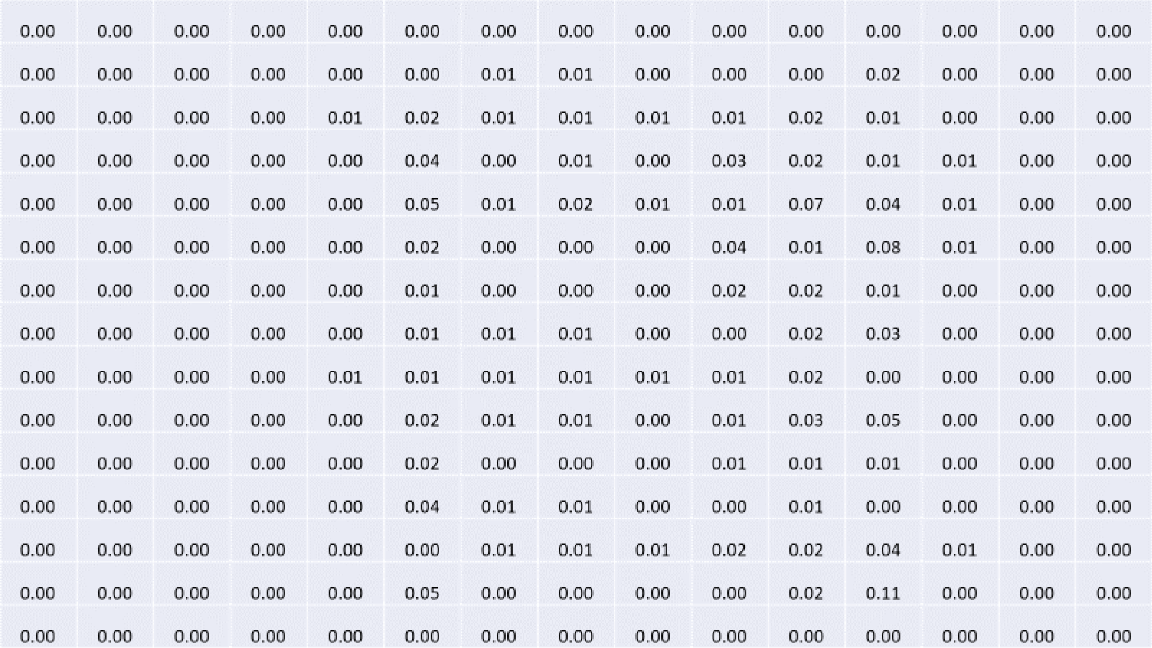
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.92	1.02	0.95	0.98	0.92	1.01	1.05	1.17	1.10	1.06	0.98	0.00	0.00
0.00	0.00	0.88	0.99	0.89	0.91	0.86	0.95	0.94	1.07	1.01	1.01	0.94	0.00	0.00
0.00	0.00	0.85	0.93	0.90	0.91	0.87	1.00	1.02	1.15	1.06	1.05	0.83	0.00	0.00
0.00	0.00	0.75	0.81	0.64	0.68	0.67	0.71	0.69	0.82	0.84	0.73	0.61	0.00	0.00
0.00	0.00	1.02	1.09	0.91	0.87	0.87	0.95	0.95	1.11	1.05	1.09	0.87	0.00	0.00
0.00	0.00	0.87	0.95	0.78	0.78	0.73	0.80	0.81	0.96	0.90	0.88	0.79	0.00	0.00
0.00	0.00	0.72	0.78	0.59	0.60	0.57	0.59	0.59	0.70	0.68	0.64	0.60	0.00	0.00
0.00	0.00	0.76	0.84	0.60	0.63	0.59	0.62	0.57	0.71	0.70	0.66	0.63	0.00	0.00
0.00	0.00	0.73	0.78	0.58	0.59	0.58	0.61	0.58	0.64	0.64	0.61	0.50	0.00	0.00
0.00	0.00	0.78	0.85	0.68	0.69	0.64	0.70	0.67	0.76	0.68	0.70	0.64	0.00	0.00
0.00	0.00	0.62	0.67	0.53	0.56	0.51	0.55	0.54	0.63	0.58	0.50	0.45	0.00	0.00
0.00	0.00	0.96	1.03	0.87	0.90	0.86	0.94	0.93	1.06	1.02	0.99	0.79	0.00	0.00
0.00	0.00	1.03	1.13	1.04	1.02	1.00	1.10	1.13	1.25	1.19	1.18	0.89	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

$$ECA_{Storm\ Surge} = \frac{\left|\{\varphi_A\}_{Structures}{}^{T}\{\varphi_x\}_{ss}\right|^2}{(\{\varphi_A\}_{Structures}{}^{T}\{\varphi_A\}_{Structures})(\{\varphi_x\}_{ss}{}^{T}\{\varphi_x\}_{ss})} =$$



0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00
0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.00	0.00
0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.20	0.00	0.18	0.00	0.00	0.33	0.00	0.00
0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.22	0.00	0.25	0.00	0.00	0.21	0.00	0.00
0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.09	0.00	0.23	0.00	0.00	0.24	0.00	0.00
0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.14	0.00	0.24	0.00	0.00	0.40	0.00	0.00
0.00	0.00	0.28	0.00	0.00	0.00	0.00	0.22	0.00	0.26	0.00	0.00	0.69	0.00	0.00
0.00	0.00	0.09	0.00	0.00	0.00	0.00	0.29	0.00	0.11	0.00	0.00	0.09	0.00	0.00
0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.12	0.00	0.08	0.00	0.00	0.15	0.00	0.00
0.00	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00
0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

$$ECA_{Flooding} = \frac{\left|\{\varphi_A\}_{Structures}{}^{T}\{\varphi_x\}_{Flood}\right|^2}{(\{\varphi_A\}_{Structures}{}^{T}\{\varphi_A\}_{Structures})(\{\varphi_x\}_{Flood}{}^{T}\{\varphi_x\}_{Flood})} =$$



0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.01	0.00	0.03	0.02	0.01	0.01	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.05	0.01	0.02	0.01	0.01	0.07	0.04	0.01	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.04	0.01	0.08	0.01	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.02	0.01	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.02	0.03	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01	0.00	0.01	0.03	0.05	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.04	0.01	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.02	0.11	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

A.3. Influence Factor Calculations

$$I_{Deforestation} = \frac{\sum ECA_{Deforestation}}{169} = 0.81$$

$$I_{Rainfall} = \frac{\sum ECA_{Rainfall}}{169} = 0.86$$

$$I_{Wind} = \frac{\sum ECA_{Wind}}{169} = 0.85$$

$$I_{Landslide} = \frac{\sum ECA_{Landslide}}{143} = 0.82$$

$$I_{Storm\ Surge} = \frac{\sum ECA_{Storm\ Surge}}{36} = 0.21$$

$$I_{Flooding} = \frac{\sum ECA_{Flooding}}{67} = 0.02$$