Resilient Islands and Installations: Interdependent Infrastructure in the US Virgin Islands

Dan Eisenberg, PhD
Research Assistant Professor | Operations Research
Deputy Director | Center for Infrastructure Defense
daniel.eisenberg@nps.edu

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Naval Postgraduate School (NPS)
America's national security research university

History Highlights

1909  Founded at U.S. Naval Academy

1951  Moved to Monterey, CA

Operations Research Curriculum

• Facilities of a graduate research university
• Faculty who work for the U.S. Navy, with clearances
• Students with fresh operational experience

FY2017:
• 65 M.S. and 15 Ph.D. programs
• 612 faculty
• 1432 resident students includes (166 international / 47 countries)
• 909 distributed learning students
Research is Part of a Broader Team Effort
Storm Characteristics

FL → PR → STT

STJ

STX → DI

St. Thomas  St. John  St. Croix

Virgin Islands

Bermuda
Storm Characteristics

St. Thomas
St. John
St. Croix

Sep 6-7
FL PR STT STX STJ DI

Irma
Storm Characteristics

[Map showing the paths of Irma and Maria from September 6-7 and September 20, respectively, passing through St. Thomas, St. John, St. Croix, and affecting the United States Virgin Islands.]

- Irma: Path from Florida through the British Virgin Islands to the United States Virgin Islands.
- Maria: Path from Puerto Rico to the United States Virgin Islands and the Virgin Islands of the Caribbean.

The map highlights the storm characteristics and the impact on the Caribbean region.
How Bad Was It?

Estimated $10B in damages
  • $6.9B to infrastructure

Roads
  • Curfew restrictions
  • Traffic lights out
  • Sevenfold increase in crashes

Electricity
  • 90% of above ground lines damaged
  • Over 50% of poles knocked down

Water
  • Reserves dropped to 3-day volume
  • Service restored after a month

Telecommunications
  • 80% of towers down
  • Public radio/tv out for months

Source: https://www.usvihurricanetaskforce.org/

DOD has recently reorganized its efforts to protect defense-related critical infrastructure under a broader program of mission assurance

Key recognition

– Assets work together as systems to provide function
– Function enables capability
– Capability supports mission

Focus needs to remain on the relationship between the infrastructure asset and the missions it supports
Resilient Islands and Installations

Infrastructure Provision within the DoD

Infrastructure Understood via Two Key Performance Indices:

- FCI – Facility Condition Index (measure of quality)
- MDI – Mission Dependency Index (measure of capability)

New DOD Requirements for Installation Resilience:

- ARMY: 2 Weeks Energy + Water (Army Directive 2017-07)
- USAF: 7 Days Energy (USAF Directive 90-17)
- USMC: 2 Weeks Energy + Water (Logistics, Comms, & Food)
Infrastructure Service Recovery Timeline – Electricity

Eligible WAPA customer restoration progress by island
% of customers restored

Hurricanes 1 Month 2 Months 3 Months
Resilience Depends on System Design – STT/STJ

Electricity Distribution System

Water Distribution System
Resilience Depends on System Design – STT/STJ

Electricity Distribution System

Water Distribution System
Relating Islands to Military Installations

Figure 3.1. Conceptual Diagram of CONUS Base Electric Power Physical Infrastructure

Relating Islands to Military Installations

Figure 3.1. Conceptual Diagram of CONUS Base Electric Power Physical Infrastructure

Needs Fuel + Controls (Telecom) to Operate

Provision of Electricity from Nearby Facilities

Needs Access to Repair (Transport)

Needs Fuel + Controls (Telecom) to Operate
Project Goals:

**Water & Electric Power Distribution:**
- Cascading failures across water and electric power systems
- Operations and management to alleviate blackout & drought impacts

**Transportation & Supply Chain:**
- Community access to disaster relief during and after hurricanes
- Drainage infrastructure condition, roadway flooding, and traffic impacts

**Internet & Fiber Backbone:**
- Hardline internet structure and vulnerability assessment
- Wireless cellphone & internet coverage post-hurricanes

**Community Engagement & Capacity Building:**
- University of the Virgin Islands – Island Infrastructure Fellowship Program
**Data Collection & Construction for St. Croix**

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>26-30 Mar</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; NPS site visit to STX, STT</td>
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<tr>
<td>11-15 Jun</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; NPS site visit to STX, STT</td>
</tr>
<tr>
<td>14-15 Jun</td>
<td>UVI/VITEMA Hazard Mitigation Workshop</td>
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<tr>
<td>22-26 Oct</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt; NPS site visit to STX, STJ, STT</td>
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<tr>
<td>24-25 Oct</td>
<td>Sandia Microgrid Workshops</td>
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<tr>
<td>24-29 Mar</td>
<td>4&lt;sup&gt;th&lt;/sup&gt; Site Visit to STX, STJ, STT</td>
</tr>
<tr>
<td>09-13 Sept</td>
<td>Planned: 5&lt;sup&gt;th&lt;/sup&gt; Site Visit &amp; 2&lt;sup&gt;nd&lt;/sup&gt; HMP Workshop</td>
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Data Collection & Construction for St. Croix
Recreating Google Maps for Disaster Relief
Recreating Google Maps for Disaster Relief

Running program: ShortestPath.py
AllPoints file: ..../Data/Working/STX/ModelPostTrip/AllPointsSTX.json
AdjList file: ../Data/Working/STX/ModelPostTrip/AdjDict.json
Origin Node: 0001
Destination Node: G025

The distance from 0001 to G025 is 31.164 km.
Linking the Infrastructure Together

- No Data on Hardline Cables Connecting Infrastructure Together
- No Data on Traffic Flow (on island and throughout the region)
Integrating Customer Demand Data Data Sets

Fixed Census Estate Data for Population Centroids
Integrating Customer Demand Data Data Sets

Fixed Census Estate Data for Population Centroids

Relating electric power demand locations to census data... goal to estimate related electric power, transportation, and water demands
Fixing Electric Power Models for Analysis

Issues with Electricity Utility Data

- Incorrect per-unit voltage for infrastructure
- Recirculation issues (mislabeled delta & wye transformers)
- Customers outside normal voltage constraints
Creating a Water Model from Disparate Data Sets

Issues with Water Utility Data
• Past EPANET model “lost”
• Mixture of GIS + AutoCAD Data → Skewed and Disjoint
• Limited Flow Meter Data – All meters destroyed in the storms
Interdependent Water-Power Failure Simulation

Excursions are denoted by originating failure events (asterisk) and their consequences across system boundaries.

Pyomo Models for Water & Electricity Distribution

Simulation engines

- WNTR includes two simulation options:

<table>
<thead>
<tr>
<th></th>
<th>DD Hydraulics</th>
<th>PDD Hydraulics</th>
<th>Water quality</th>
<th>Leaks</th>
<th>Network options</th>
<th>Simulation options</th>
<th>Control options</th>
<th>Start/Stop</th>
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<td>✓</td>
<td>✓ Emitters</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>WNTRSimulator</td>
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<td></td>
<td>Almost all</td>
<td>Almost all</td>
<td>✓</td>
<td>✓</td>
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</table>

DD and PDD hydraulics

Leak model

\[
d = \begin{dcases}
0 & p \leq P_0 \\
D_f \left( \frac{p-P_0}{P_f-P_0} \right)^{\frac{1}{2}} & P_0 \leq p \leq P_f \\
D_f & p \geq P_f
\end{dcases}
\]

\[
d_{leak} = C_d A p^n \sqrt{\frac{2}{\rho}}
\]

Simulation engines

- WNTR includes two simulation options:
  - EpanetSimulator
  - WNTRSimulator

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Approved for public release. Distribution is unlimited.

ASSESSING THE OPERATIONAL RESILIENCE OF ELECTRICAL DISTRIBUTION SYSTEMS

Clark Petri
Lieutenant Commander, United States Navy
B.S., Oregon State University, 2005

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL

September 2017
Water Supply Distribution System

Note: Pumps and valves are located at a variety of locations throughout the distribution system.
Water Supply Distribution System

Note: Pumps and valves are located at a variety of locations throughout the distribution system.

Legend

- E = Nodal Elevation (m)
- BD = Base Demand (m³/s)
- D = Pipe Diameter (m)
- L = Pipe Length (m)
- R = H-W Roughness

Electricity generation, transmission, and distribution

Source: Adapted from National Energy Education Development Project (public domain)
Water System

Pressure and Demand at Demand Node

Power System
Water System

Power System
A more realistic (USVI) water distribution system

Water Demand Node

#1 Pump Flow Rate

Tank Flow Rate

#2 Pump Flow Rate

Tank Height

#1 Pump Flow Rate
IEEE 13-bus electricity distribution network
Current Goals: Setting a Baseline Through Past Events
March 2019 STX West Coast Water Outages
1. Contentment Pumping Station – Pumps Stop Working at Full Capacity
2. Concordia Pumping Station – Circuit Breaker Blew / Offline
3. Kingshill Tank Drains – Frederiksted Loses Water
4. New Pumps Installed & Tested at All Major Pumping Stations
5. Water Level in Kingshill Tank Regained – Frederiksted with water
6. Island-wide Blackout – Loss of 2 Feet at Kingshill
Next Steps:

**Water & Electric Power Distribution:**
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Backup Slides
# The Mission Dependency Index


## Interruptibility Score

<table>
<thead>
<tr>
<th>None (N)</th>
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<tbody>
<tr>
<td>Urgent (U)</td>
</tr>
<tr>
<td>Brief (B)</td>
</tr>
<tr>
<td>Short (S)</td>
</tr>
<tr>
<td>Prolonged (P)</td>
</tr>
</tbody>
</table>

## Relocatability / Replaceability Score

<table>
<thead>
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<th>Impossible (I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely Difficult (X)</td>
</tr>
<tr>
<td>Difficult (D)</td>
</tr>
<tr>
<td>Possible (P)</td>
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</tbody>
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**Generation – Oversized and Inefficient**

- Flat electric power needs across the entire year.
- Oversized generation turbines are used in inefficient ways.
  Susceptible to demand & volt-freq imbalances

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### Gas Turbine Generators STX Power System

<table>
<thead>
<tr>
<th>Unit</th>
<th>Fuel Type</th>
<th>Capacity (MW)</th>
<th>Unit Type</th>
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<tbody>
<tr>
<td>10</td>
<td>#2 Fuel Oil</td>
<td>10</td>
<td>Worthington STG</td>
</tr>
<tr>
<td>11</td>
<td>#2 Fuel Oil</td>
<td>19.1</td>
<td>GE STG</td>
</tr>
<tr>
<td>16</td>
<td>Dual (#2 or LPG)</td>
<td>20.9</td>
<td>GE MS5001P CT</td>
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<tr>
<td>17</td>
<td>Dual (#2 or LPG)</td>
<td>21.9</td>
<td>Alstom</td>
</tr>
<tr>
<td>19</td>
<td>Dual (#2 or LPG)</td>
<td>22.5</td>
<td>GE5001</td>
</tr>
<tr>
<td>20</td>
<td>Dual (#2 or LPG)</td>
<td>22.5</td>
<td>GE5001</td>
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</table>

### Blackstart Emergency Generators

<table>
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<th>Unit</th>
<th>Fuel Type</th>
<th>Capacity (MW)</th>
<th>Unit Type</th>
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<tbody>
<tr>
<td>--</td>
<td>#2 Fuel Oil</td>
<td>0.75</td>
<td>GE6F09802</td>
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Transmission & Distribution –
Single Generation Plant Leaves Communities Vulnerable

- Centralized electricity Production
- Aging generation, transmission, and distribution infrastructure
Critical Loads – (Mis)match with Community Needs

- Community industrial / commercial and residential loads have regular characteristics
- Some critical loads match community needs
Critical Loads – (Mis)match with Community Needs

- Community industrial / commercial and residential loads have regular characteristics.
- Some critical loads do not match community needs.
### Economics – Volatile and Expensive Electricity Prices

- Imported fuels are expensive and the price is volatile
- Customer electricity prices are remarkably high leading (~$0.40 per kWh).
- Defections are common

#### Revenues (in thousands)

<table>
<thead>
<tr>
<th></th>
<th>2018 (ending 10/01)</th>
<th>2017</th>
<th>2016</th>
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<tbody>
<tr>
<td></td>
<td>$</td>
<td>% Total</td>
<td>$</td>
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<tr>
<td>Levelized Energy Adjustment Clause (LEAC)</td>
<td>129,668</td>
<td>57</td>
<td>114,562</td>
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<tr>
<td>All Other (incl. sales and surcharges)</td>
<td>95,927</td>
<td>43</td>
<td>83,523</td>
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<tr>
<td>Total</td>
<td>225,595</td>
<td>--</td>
<td>198,085</td>
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</table>
Water Distribution – Unfortunately Similar Issues

- Centralized production
- Aging infrastructure
- Conflicting consumer demands
- High costs
- Consumer defections