Understand Today:
Critical Infrastructure Function and Vulnerability in the USVI

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Dr. Daniel Eisenberg, Deputy Director
Center for Infrastructure Defense
Operations Research Department
Naval Postgraduate School, Monterey, CA

USVI Hazard Mitigation and Resilience Workshop
November 2020
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

FY2018/19:
- 65 M.S. and 15 Ph.D. programs
- 644 faculty
- 1459 resident students includes (144 international / 48 countries)
- 853 distributed learning students
We are experts in interdependent infrastructure modeling and analysis. We support infrastructure system operations, recovery, and planning.
USVI Modeling & Analysis: Recent NPS Graduates

MAJ Elad Bengigi, Israel Defense Forces
MS SE, Technion 2018
MS OR, Sept 2020
Road Networks

LCDR Robert Routley, SC, USN
Naval Supply Officer
MS OR, Sept. 2020
Supply Chains STT, STJ

LCDR Brendan Bunn, PE, USN
Naval Civil Engineer Corps
MS OR, Sept. 2018
Water-Power Models

LCDR Jeff Good, SC, USN
Naval Supply Officer
MBA, National University, 2008
MS OR, Sept. 2019
Supply Chain STX

Ens Andrew Borgdorff, USN
USNA, June 2019
MS OR, Dec. 2020
Water on STT, STJC

Maj Brian Moeller, USMC
MS OR, Dec. 2020
Internet on STT

Cpt Dominik Wille, German Army
MS EE, Universität de Bundeswehr, 2012
MS OR, Dec. 2019
Power-Water Models

Capt Bill Wine, USMC
MS OR, Dec. 2020
Cell Towers
Operational Resilience Analysis and Capacity Building in the US Virgin Islands


Project Abstract: This project builds on preliminary work to provide modeling, analysis, and subject matter expertise to the Infrastructure Systems (IS) Recovery Support Function (RSF) and the Community Planning and Capacity Building RSF following Hurricane Irma and Hurricane Maria in the territory of the US Virgin Islands. Specifically, this project proposes (1) ongoing modeling and analysis of interdependent infrastructure systems within the territory, with emphasis on assessing and improving their operational resilience; (2) support for the development of a next-generation hazard mitigation and resilience plan in the territory; and (3) capacity building efforts via the development of an education and training pipeline for knowledgeable professionals who understand and think about hazard mitigation and operational resilience of the USVI in everything they do. This project explicitly supports several other complementary efforts, particularly those hosted at the University of the Virgin Islands.

Simulation Optimization for Operational Resilience of Interdependent Water-Power Systems in the US Virgin Islands.


This work studies the water and power distribution systems on the island of St. Croix (STX) to predict the outcome of interdependent water-power failure events and recommend system hardening and protection activities. As the storms revealed, loss of electricity on STX can also lead to loss of pumping stations that distribute water. During these situations operators rely on water storage tanks to serve communities until electricity and pumps return to service. The goal of this thesis is to model how water-power failures happen and recommend ways to prevent them by answering the following questions:
Partners Working to Improve Infrastructure Resilience

Federal

[Logos of various federal agencies]

Regional

[Logos of regional partners]

Local

[Logos of local partners]

Our work is a “Joint” effort in partnership with a variety of organizations.
A Story in Two Parts...

Day 1

How are we doing?
(System Function & Vulnerability)

How does it work?
What can go wrong?

How does it work?
Rocks, STT
Flood Impacts

Structure, function, operations, mgmt., etc.
Assumptions about our systems

Day 2

Where are we going?
(Risk & Resilience)

What do we want?
What do we need to do?

What do we want?
Responses, actions, goals, etc.
Assumptions about our future

What do we need to do?
Processes, capacities, capabilities, etc.
Assumptions about ourselves

Backgrounds, beliefs, biases, etc.
Assumptions about our needs

Roads, STT
Flood Impacts

Robustness: System continues to function as intended
Extensibility: System function stretches to support new needs
Adaptability: System changes to function in new ways
A Story in Two Parts...

Day 1

How are we doing? (System Function & Vulnerability)

How does it work? → What can go wrong?

Structure, function, operations, mgmt., etc. → Flood Impacts

Assumptions about our systems

Day 2

Where are we going? (Risk & Resilience)

What do we want? → What do we need to do?

Responses, actions, goals, etc. → Processes, capacities, capabilities, etc.

Assumptions about our future

Assumptions about ourselves
How are we doing...? Analysis of Critical Infrastructure

Key Recognition: Need an *Operational View* of Infrastructure

- **Systems Modeling**: We model system function
  
  - Assets → Systems → Function → Capability → Mission
Key Recognition: Need an *Operational View* of Infrastructure

• **Systems Modeling**: We model system function
  
  \[
  \text{Assets} \rightarrow \text{Systems} \rightarrow \text{Function} \rightarrow \text{Capability} \rightarrow \text{Mission}
  \]

We build models to assess the capability of a system to deliver service under different scenarios:

• How well does the system perform during normal operation?
• How well does the system perform when stressed?
  
  • Loss of one or more assets? (e.g., from failures, hurricanes)
  • Extreme demands? (e.g., during drought)
How are we doing...? Analysis of Critical Infrastructure

Key Recognition: Need an *Operational View* of Infrastructure

- **Systems Modeling:** We model system function
  - Assets $\rightarrow$ Systems $\rightarrow$ Function $\rightarrow$ Capability $\rightarrow$ Mission

Modeling & Analysis

We build models to assess the capability of a system to deliver service under different scenarios:

- How well does the system perform during normal operation?
- How well does the system perform when stressed?
  - Loss of one or more assets? (e.g., from failures, hurricanes)
  - Extreme demands? (e.g., during drought)

Defining “mission success” is for stakeholders, not modelers
Translate Stakeholder Issues into Research Questions

Create Data, Models, and Analysis Tools to Inform Stakeholder Issues

Work with Stakeholders to Turn Analysis into Decisions

Co-Develop Research Projects with CID Faculty, Staff, and Project Stakeholders
Electric Power: STX Power Grid Hurricane Vulnerability

Q: What is the Vulnerability of STX Grid to Hurricanes?

- Worked with Sandia, Updated STX Data Sets from VI WAPA
- Conducted STX Risk Analysis to Predict Impacts of Power Infrastructure Failures

Results: Determined Optimal Hurricane Hardening Strategy

Cpt Dominik Wille, German Army
Simulation-Optimization for Operational Resilience of Interdependent Water-Power Systems in the US Virgin Islands, Dec. 2019
Electric Power:

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?
Electric Power:

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?
Electric Power:

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?

Generation → Transmission → Distribution

Source: Adapted from National Energy Education Development Project (public domain)
Electric Power:

- How does it work?
- What can go wrong?
- What do we want?
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Electric Power:

- Generation → Transmission → Distribution

Source: Adapted from National Energy Education Development Project (public domain)
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- How does it work?
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- What do we want?
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Electric Power: Generation → Transmission → Distribution

- Generation: power plant generates electricity
- Transmission: transmission lines carry electricity long distances
- Distribution: distribution lines carry electricity to houses

- Residential solar
- Backup generator

Source: Adapted from National Energy Education Development Project (public domain)
Electric Power:

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?

Electricity flows through the following stages:

1. **Generation**: Power plant generates electricity.
2. **Transmission**: Transmission lines carry electricity long distances.
3. **Distribution**: Distribution lines carry electricity to houses.

---

**Source**: Adapted from National Energy Education Development Project (public domain)
Electric Power:

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?

Electric Power:

Generation $\rightarrow$ Transmission $\rightarrow$ Distribution

- solar farm
- wind farm
- backup generator
- residential solar

Source: Adapted from National Energy Education Development Project (public domain)
Electric Power:

Generation → Transmission → Distribution

- Solar farm
- Wind farm
- Backup generator
- Residential solar

Source: Adapted from National Energy Education Development Project (public domain)
How Vulnerable is the STX Grid with wooden poles only?

Results From Hurricane Simulations:
Category 1 (74-95 mph): No Blackout
Category 2 (96-110 mph): Feeder Dependent
Category 3 (111-129 mph): Full Blackout

Power Line Vulnerability Depends on Design:
- Feeders 02a, 06a, & 10b most vulnerable
- Feeders 01a & 05a most robust
How Can We Protect the STX Grid?
How Can We Protect is the STX Grid?: **Poles + Undergrounding**

Results From Hurricane Simulations:
- Category 3 (Poles): **Good**
- Category 3 (Underground): **Better**
- Category 3 (Combined): **Best (No Load Shed)**

Power Line Vulnerability Depends on Design:
- Feeders 01a & 05a better with poles
- All other feeders better with undergrounding
Supply Chains: STT & STJ Access to Critical Supplies

Q: Can Communities Access Supplies After Disaster?

Developed Data & Network Model for Last Mile Supply Chain

Conducted STT & STJ Risk Analysis to Predict Impact of Flooding on Roads

Results: Identified Communities that Cannot Access Supplies

LCDR Robert Routley, USN
An Operational Model of the Critical Supply Chain for St. Thomas and St. John, Sept. 2020
Supply Chains: STT & STJ Access to Critical Supplies

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?
Supply Chains: STT & STJ Access to Critical Supplies

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?

Port

Stores
Supply Chains: STT & STJ Access to Critical Supplies

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?
Supply Chains: STT & STJ Access to Critical Supplies

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- How does it work?
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- What do we want?
- What do we need to do?

Congestion: Is there sufficient road capacity?
Supply Chains: STT & STJ Access to Critical Supplies

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?

Vulnerable populations: Who is most affected by long drive times?

Congestion: Is there sufficient road capacity?
Supply Chains: STT & STJ Access to Critical Supplies

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?

Flooding: What happens when roads are blocked?

Congestion: Is there sufficient road capacity?

Vulnerable populations: Who is most affected by long drive times?
How Vulnerable is the STJ Supply Chain to Flooding?

- Normal w/ Curfew
- Expected
- Worst-Case
How Vulnerable is the STJ Supply Chain to Flooding?

- Normal with Curfew
- Expected
- Worst-Case

Supply Access?
How Vulnerable is the STT Supply Chain to Flooding?

- **Normal w/ Curfew**
- **Expected**
- **Worst-Case**
How Vulnerable is the STT/STJ Supply Chain to Flooding?

Island Stores Unreachable for Resupply by the Port Stranded People who cannot Access Supplies

<table>
<thead>
<tr>
<th>Island</th>
<th>Stores Unreachable for Resupply by the Port</th>
<th>Stranded People who cannot Access Supplies</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. John</td>
<td>12 (All Stores)</td>
<td>250 (~5%)</td>
</tr>
<tr>
<td>St. Thomas</td>
<td>8 (Eastern STT)</td>
<td>4,656 (~9%)</td>
</tr>
</tbody>
</table>
Water: Predicting Water Demands Pre- and Post-Hurricanes

Q: How to Predict Pipe, Cistern, etc. Water Demands

Identifying Key Issues / Questions

Collect / Curate Data

Develop Model + Tools

Apply Tools for Analysis

Communicate Results

Integrating Customer & Weather Data Sets

Developing Demand Prediction Model for All Customer Types

Results: Statistical Models to Estimate Pre- and Post-Storm Demands

ENS Andrew Borgdorff, USN

A Demand and Distribution Model for Potable Water in the USVI; June 2020
Water: Predicting Water Demands Pre- and Post-Hurricanes

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?
PRODUCTION → STORAGE → DISTRIBUTION → STORAGE → CONSUMPTION

- rainwater
- seawater
- groundwater

- residences
- business
- government
- hotels & resorts
- industry
- agriculture
PRODUCTION → STORAGE → DISTRIBUTION → STORAGE → CONSUMPTION

rainwater

seawater → reverse osmosis

groundwater

WAPA

grocery stores

residences

business

government

hotels & resorts

industry

agriculture

rainwater catchment

truck delivery

pipeline delivery
- Rainwater catchment
- Truck delivery
- Pipeline delivery
- Customer pickup
- Local desalination

PRODUCTION → STORAGE → DISTRIBUTION → STORAGE → CONSUMPTION

- Rainwater
- Seawater
- Groundwater
- Reverse osmosis

- Residences
- Business
- Government
- Hotels & Resorts
- Industry
- Agriculture

WAPA

- rainwater catchment
- truck delivery
- pipeline delivery
- customer pickup
- local desalination
What can go wrong?
What can go wrong?
What can go wrong?

Problems with potable water pipeline system.

- rainwater catchment
- truck delivery
- pipeline delivery

PRODUCTION → STORAGE → DISTRIBUTION → STORAGE → CONSUMPTION

- residences
- business
- government
- hotels & resorts
- industry
- agriculture
**What can go wrong?**

Problems with potable water pipeline system. Can perhaps be mitigated by truck delivery.
What can go wrong?

Long-term drought
What can go wrong?

Long-term drought

Can production and distribution meet demand?

What can go wrong?

Long-term drought

Can production and distribution meet demand?

What can go wrong?

Long-term drought

Can production and distribution meet demand?

What can go wrong?

Long-term drought

Can production and distribution meet demand?
How Well can We Predict Water Demands?:

SARIMA(1,0,0)(0,1,1,12)

STJ Volume Monthly  Fitted Values  Predicted Values

Volume (Gallons)

Date

2013  2014  2015  2016  2017

Hurricane

Pre-Storm  Post-Storm
How Well can We Predict Water Demands?: Poorly

Best-of-breed models perform poorly in the presence of surprise.
But... Demand for Water Trucks has Strong Correlation to Rainfall

<table>
<thead>
<tr>
<th>Average Rainfall Over Previous 45-Days (inches)</th>
<th>Mean Daily Truck Sales (gallons)</th>
<th>Equivalent Number of Water Trucks</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 0.0329</td>
<td>75,360</td>
<td>18.8</td>
</tr>
<tr>
<td>0.0329 to 0.0373</td>
<td>37,292</td>
<td>9.3</td>
</tr>
<tr>
<td>0.0373 to 0.0778</td>
<td>11,043</td>
<td>2.8</td>
</tr>
<tr>
<td>0.0778 and Greater</td>
<td>4,886</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Capt William Wine, USMC

Cell Phone Network Resilience in the US Virgin Islands; June 2020
Telecom: Robustness of the USVI Cell Phone Network

- How does it work?
- What can go wrong?
- What do we want?
- What do we need to do?
Telecom: Which Cell Towers Serve Public Safety?:

Free Space Loss
Ground Reflections Loss
Diffraction and Foliage Loss
Simple Diffraction Model
Multiple Losses
Telecom: Which Cell Towers Serve Public Safety?: 1, 17, 20, & 2

CAI Categories
1: K-12 School
2: Library
3: Medical
4: Public Safety
5: University
6: Other Gov
7: Other NGO

<table>
<thead>
<tr>
<th>Tower</th>
<th>CAI 1</th>
<th>CAI 2</th>
<th>CAI 3</th>
<th>CAI 4</th>
<th>CAI 5</th>
<th>CAI 6</th>
<th>CAI 7</th>
<th>Total</th>
</tr>
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<tbody>
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<td>STT-1</td>
<td>14</td>
<td>0</td>
<td>11</td>
<td>12</td>
<td>1</td>
<td>50</td>
<td>2</td>
<td>90 (49.2%)</td>
</tr>
<tr>
<td>STT-6</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>15 (8.2%)</td>
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<tr>
<td>STT-9</td>
<td>11</td>
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<td>2</td>
<td>6</td>
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<td>24</td>
<td>1</td>
<td>45 (24.6%)</td>
</tr>
<tr>
<td>STT-15</td>
<td>12</td>
<td>2</td>
<td>9</td>
<td>5</td>
<td>0</td>
<td>60</td>
<td>4</td>
<td>92 (50.3%)</td>
</tr>
<tr>
<td>STT-17</td>
<td>27</td>
<td>2</td>
<td>11</td>
<td>12</td>
<td>1</td>
<td>80</td>
<td>6</td>
<td>139 (76.0%)</td>
</tr>
<tr>
<td>STT-20</td>
<td>24</td>
<td>3</td>
<td>13</td>
<td>14</td>
<td>1</td>
<td>77</td>
<td>8</td>
<td>140 (76.5%)</td>
</tr>
<tr>
<td>STT-24</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>10</td>
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<td>16 (8.7%)</td>
</tr>
<tr>
<td>STT-33</td>
<td>9</td>
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<td>18</td>
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<td>33 (18.0%)</td>
</tr>
<tr>
<td>STT-34</td>
<td>12</td>
<td>2</td>
<td>8</td>
<td>4</td>
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<td>50</td>
<td>3</td>
<td>79 (43.2%)</td>
</tr>
<tr>
<td>STT-35</td>
<td>16</td>
<td>2</td>
<td>9</td>
<td>4</td>
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<td>59</td>
<td>6</td>
<td>96 (52.5%)</td>
</tr>
<tr>
<td>STT-36</td>
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<td>2</td>
<td>5</td>
<td>0</td>
<td>14</td>
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<td>34 (18.6%)</td>
</tr>
<tr>
<td>STJ-2</td>
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<td>0</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>14 (7.7%)</td>
</tr>
<tr>
<td>STJ-3</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1 (0.5%)</td>
</tr>
<tr>
<td>All CAIs</td>
<td>39</td>
<td>3</td>
<td>14</td>
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Telecom: Which Cell Towers Serve Public Safety?: 1, 17, 20, & 2

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CAI Categories
1: K-12 School
2: Library
3: Medical
4: Public Safety
5: University
6: Other Gov
7: Other NGO

“Good”  
“Medium”  
None
Key Messages

Our work in the USVI support HMRP in multiple areas:

- **Power**: Hurricane Hardening
- **Roads**: Supply Chain Mgmt., Effects of Intersection Design + Network Upgrades
- **Telecom**: Wireless Vulnerability, Fiber Cuts
- **Water**: Water Sensing, Water Network Resilience

An operational view of infrastructure function is vital to answering key questions:

- ✓ How does it work?
- ✓ What can go wrong?
- ❑ What do we want? stakeholder values
- ❑ What do we need to do? manage risk, build resilience (tomorrow’s discussion)
A Story in Two Parts...

Day 1

How are we doing? (System Function & Vulnerability)

- How does it work?
- What can go wrong?
- Structure, function, operations, mgmt., etc.
- Assumptions about our systems

Day 2

Where are we going? (Risk & Resilience)

- What do we want?
- What do we need to do?
- Responses, actions, goals, etc.
- Processes, capacities, capabilities, etc.
- Assumptions about our future
- Assumptions about ourselves

Roads, STT

Flood Impacts

Backgrounds, beliefs, biases, etc.
- Assumptions about our needs
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Operational Resilience Analysis and Capacity Building in the US Virgin Islands


Project Abstract: This project builds on preliminary work to provide modeling, analysis, and subject matter expertise to the Infrastructure Systems (IS) Recovery Support Function (RSF) and the Community Planning and Capacity Building RSF following Hurricane Irma and Hurricane Maria in the territory of the US Virgin Islands. Specifically, this project proposes (1) ongoing modeling and analysis of interdependent infrastructure systems within the territory, with emphasis on assessing and improving their operational resilience; (2) support for the development of a next-generation hazard mitigation and resilience plan in the territory; and (3) capacity building efforts via the development of an education and training pipeline for knowledgeable professionals who understand and think about hazard mitigation and operational resilience of the USVI in everything they do. This project explicitly supports several other complementary efforts, particularly those hosted at the University of the Virgin Islands.

REFERENCES