Case Studies of Infrastructure Resilience in the VI

David Alderson, PhD
Daniel Eisenberg, PhD
LCDR Jeff Good, USN
Cpt Dominik Wille, GER
Operations Research Department
Center for Infrastructure Defense
Naval Postgraduate School

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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
What is Operations Research?

- Operations Research (OR) is the science of helping people and organizations make better decisions using
  - mathematical models, statistical analyses, simulations
  - analytical reasoning and common sense

to the understanding and improvement of real-world operations.

Infrastructures are systems of components that work together to achieve a desired function. The consequence of infrastructure disruption is the loss of that function.
Motivation: Concern about accidents, failures, natural hazards, attacks on critical infrastructures

How to Think About Critical Infrastructure

• A list of *assets*

• An interconnected (network) *system* that works to achieve a particular function
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How to Think About Critical Infrastructure

• A list of assets

• An interconnected (network) system that works to achieve a particular function

We want to make our operations (e.g., lifeline systems) resilient to disruptive events.

We need our infrastructure systems to continue to function even when “bad things” happen.
Operations Research 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
Operations Research Analysis of Critical Infrastructure

Key Recognition: Need an *Operational View* of Infrastructure

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  **Modeling**

  We build models to assess the capability of a system to deliver service under different scenarios:
  - Loss of assets / components – due to failure, etc
  - Given the ability of the system operator to adapt (e.g., rebalance flows, change operations)
  - In order to achieve ”mission success”
Operations Research Analysis of Critical Infrastructure

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Defining ”mission success” is for stakeholders, not modelers
Operations Research Analysis of Critical Infrastructure

Key Recognition: Need an *Operational View* of Infrastructure

- **Systems Modeling**: We model system function
  - Assets → Systems → Function → Capability → Mission
  - We assess degradation from loss of sets of components

- **Red Teaming**: We identify worst-case disruptions

- **Blue Teaming**: We identify optimal investments to maximize system resilience

We connect models of individual infrastructures together to assess dependencies and “full spectrum” threats.

**NPS Center for Infrastructure Defense**: [www.nps.edu/cid](http://www.nps.edu/cid)

**USVI project page**: [faculty.nps.edu/dlalders/usvi](http://faculty.nps.edu/dlalders/usvi)
Today’s Agenda

• Provide an overview of our ongoing modeling and analysis of lifeline critical infrastructure systems in the VI

• Discuss the role of this work for hazard mitigation and resilience

• (to include capacity building and include workforce development)
Our USVI work: part of a broader team effort
# Our USVI work: current project timeline

<table>
<thead>
<tr>
<th>Date Range</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>27 Feb 2018</td>
<td>Project Start</td>
</tr>
<tr>
<td>26-30 Mar</td>
<td><strong>NPS site visit to STX, STT</strong></td>
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<tr>
<td>11-15 Jun</td>
<td><strong>NPS site visit to STX, STT</strong></td>
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<td><strong>22-26 Oct</strong></td>
<td><strong>NPS site visit to STX, STJ, STT</strong></td>
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<tr>
<td>01 Dec</td>
<td>NPS Technical Report: Preliminary Analysis</td>
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<tr>
<td>9-11 Dec</td>
<td>UVI site visit to Stanford, NPS</td>
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<td><strong>24-29 Mar 2019</strong></td>
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<td>NPS site visit (telecom/internet)</td>
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<td>Spring 2020</td>
<td>Launch of UVI course on infrastructure resilience</td>
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Our USVI work: several related research efforts

**Effort 1** - Modeling and analysis of interdependent critical infrastructure systems
- Energy (emphasis on electric power)
- Water (emphasis on potable storage and distribution)
- Transportation & Supply Chains
- Telecommunications & Internet

**Effort 2** - Support for development of a new Hazard Mitigation and Resilience Plan
- in partnership with UVI / VITEMA (POC: Kim Waddell, Greg Guannel)

**Effort 3** - Capacity building & workforce development program
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Report Contributions: an integrated view of “how stuff works”

1. Explaining the structure, function, and tensions associated with critical infrastructure that were chronic problems *prior* to the hurricanes.
2. Documenting hurricane response, recovery, and mitigation activities for these infrastructure systems *after* the hurricanes.
3. Discussing these changes in the context of potential barriers to resilience.
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Effort 1 - Modeling and analysis of interdependent critical infrastructure systems

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Electricity generation, transmission, and distribution

power plant generates electricity

transmission lines carry electricity long distances

distribution lines carry electricity to houses

transformers on poles step down electricity before it enters houses

transformer steps up voltage for transmission

neighborhood transformer steps down voltage

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

(a)
Physical Grid Data:
• Generators (supply sites)
• Lines
• Transformers
• Buses (demand sites)
• Thermal limits, voltage bounds, impedance, etc.

Scenario Data:
• Generation capacity
• Customer demands
• Priority per demand
• Availability/damage to grid components

How “best” to operate the system:
• generation, switches to minimize unmet demand
• delivered flows
• who can get power, who cannot
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ELEC POWER MODEL

How “best” to operate the system:
- generation, switches to minimize unmet demand
- delivered flows
- who can get power, who cannot
St. Croix Electric Power Distribution Operator Model

- **System Size**: Power Line Segments (40k), Customers (17k), Transformers (3.8k)
- **Physics**: 3-Phase AC Power Flow (unbalanced)
- **Model Objective**: Dispatch Power to Minimize Customer Load Shed
- **Results**: Power Flow (direction & quantity), Customers Served

Questions that Can be Answered (among others):
- Optimal Dispatch for Different Amounts of Generation and Customer Load
- Customer Impacts from Component Failures (load shed)

We present results in the form of interactive web-based maps.
Water Supply Distribution System

Note: Pumps and valves are located at a variety of locations throughout the distribution system.
Physical Network Data:
- Production (supply sites)
- Pipes, junctions, valves
- Pumps, curves
- Elevations, diameters, etc.

Scenario Data:
- Production capacity
- Initial tank levels
- Customer demands + priorities
- Availability/damage

How “best” to operate the system:
- Pumps, valves, pressures to minimize unmet demand
- Delivered flows
- Who can get water, who cannot

Water Supply Distribution System

Legend
- E = Nodal Elevation (m)
- BD = Base Demand (m³/s)
- D = Pipe Diameter (m)
- L = Pipe Length (m)
- R = H-W Roughness
Physical Network Data:
- Generation (supply sites)
- Pipes, junctions, valves
- Pumps, curves
- Elevations, diameters, etc.

Scenario Data:
- Generation capacity
- Tank levels
- Customer demands + priorities
- Availability/damage

How “best” to operate the system:
- Pumps, valves, pressures to minimize unmet demand
- Delivered flows
- Who can get water, who cannot

Notional Failure Scenario
St. Croix Water Distribution *Operator Model*

- **System Size:** Pipes (847), Pumps (7), Junctions (670), Tanks (6), Reservoirs (1)
- **Physics:** Demand (EPANET) & Pressure Dependent (WNTR) Hydraulic Balancing
- **Model Objective:** Extended Period Simulation of Water Flow and Headloss
- **Results:** Pipeline Flow, Pump Operations, Tank Levels, Customers Served

Questions that Can be Answered (among others):
- Optimal Pump Settings and Tank Levels to Serve Customers
- Customer Impacts of Component Failures (water service availability)

We present results in the form of interactive web-based maps.
Notional Failure Scenario
Power Simulation-Optimization:
- **Simulation**: How do hurricanes impact customers & water pumping stations?
- **Optimization**: What power infrastructure hardening is best for both electricity and water systems?

Water Simulation-Optimization:
- **Simulation**: How long can the water system provide service without electricity?
- **Optimization**: Find critical pump & tank operations to maximize water service availability during blackouts.
Our USVI work: several related research efforts

Effort 1 - Modeling and analysis of interdependent critical infrastructure systems

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Goals:

- Assess how USVI food supply chains and transportation systems perform during normal and post-hurricane conditions
- Consider new courses of action that minimize household travel time, maximize supply chain access, and support faster recovery

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Understand transportation infrastructure to support:

• Movement of goods into ports and onto stores via surface roads
• Movement of people from their homes to stores via surface roads

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Understand transportation infrastructure to support:

• Movement of goods into ports and onto stores via surface roads

• Movement of people from their homes to stores via surface roads

Quantify impacts of:

• Imposed curfews

• Surface road restrictions or blockages

• Alternative relief locations

Objective: \textit{Maximize} supply chain access

Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW
RT TIME (RTT)
Understanding Traffic Demand (Congestion): Delivery Model

Objective: **Maximize** supply chain access
Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW

RT TIME (RTT) = Load
Objective: **Maximize** supply chain access

Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW

RT TIME (RTT) = **Load** + **Outbound**

**Understanding Traffic Demand (Congestion): Delivery Model**
Objective: *Maximize* supply chain access
Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW
RT TIME (RTT) = Load + **Outbound** + Unload
Objective: **Maximize** supply chain access

Metric: Number of ROUND TRIPS (RT) per DAY/CURFEW WINDOW

$$RT\ TIME\ (RTT) = \text{Load} + \text{Outbound} + \text{Unload} + \text{Return}$$
Understanding Traffic Demand (Congestion): Customer Model

Objective: Minimize household travel time
Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW RTT
Objective: \textit{Minimize} household travel time
Metric: \textsc{Round Trip Time (RTT)} no longer than \textsc{Curfew Window}

\[ \text{RTT} = \text{Outbound} \]
Objective: *Minimize* household travel time
Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW
RTT = **Outbound** + **Service Time**

**Understanding Traffic Demand (Congestion): Customer Model**
Objective: *Minimize* household travel time

Metric: ROUND TRIP TIME (RTT) no longer than CURFEW WINDOW

\[ \text{RTT} = \text{Outbound} + \text{Service Time} + \text{Return} \]
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

Port

Stores

Homes
Understanding Traffic Demand (Congestion): Combined Model

Shared: Roads and Stores

Is there sufficient road capacity?
Understanding Traffic Demand (Congestion): Combined Model

**Shared:** Roads and Stores

Is there sufficient road capacity?
Are stores optimally stocked for expected demand?
Understanding Traffic Demand (Congestion): Combined Model

**Shared**: Roads and Stores

Is there sufficient road capacity?
Are stores optimally stocked for expected demand?
Who is most affected by long drive times?
On-going Work: Sponsor Interest
What ifs?
On-going Work: Sponsor Interest

What ifs?
Roads are blocked by electric poles?
Partially blocked?
On-going Work: Sponsor Interest

What ifs?
Roads are blocked by electric poles?
Partially blocked?
Port inaccessible?
On-going Work: Sponsor Interest

What ifs?
Roads are blocked by electric poles?
Partially blocked?
Port inaccessible?
New Relief Point? Distribution Point?
St. Croix Road Transportation *Operator Model*

- **Traffic origins**: 233 Estates + 1 Port
- **Traffic destinations**: 38 (grocery, gas, hardware)
- **Road network**: 2,353 road segments (3 types)
- **Equilibrium model**: given available roads and congestion, how *should* traffic flow between origins and destinations to minimize overall travel time

**Road Network Data:**
- Estates + Populations
- Roads: Types, Capacities, Distances
- Store locations
- Relief locations

**Scenario Data:**
- Traffic demands
- Availability/damage to road segments

The “best” routes for traffic:
- routes to minimize travel times
- traffic flows
- round trip times
- time lost in congestion
Results: Insufficient Capacity with “Selfish” Routing

Road Network Data:
- Estates + Populations
- Roads: Types, Capacities, Distances
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TRANSPORTATION MODEL
The “best” routes for traffic:
- routes to minimize travel times
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- round trip times
- time lost in congestion

LEGEND:
- Ports
- Gas Stations
- Grocery Stores
- Hardware/Misc.
Road Network Data:
• Estates + Populations
• Roads: Types, Capacities, Distances
• Store locations
• Relief locations

Scenario Data:
• Traffic demands
• Availability/damage to road segments

The “best” routes for traffic:
• routes to minimize travel times
• traffic flows
• round trip times
• time lost in congestion

TRANSPORTATION MODEL

Notional Curfew Scenario

Results: Routing of Longest Travel Times for All Store Types
Our work in the USVI: several related research efforts

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– Water (emphasis on potable storage and distribution)
– Transportation & Supply Chains
– Telecommunications & Internet
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- **Telecommunications & Internet**

*Telecommunication systems are different* from other public infrastructures:

- prevalence of private companies who tend to hide system details
- virtual nature of internet connectivity and related “cloud-based” services

Result: need to combine measurement, modeling, and analysis

**Our Focus**: connectivity models of Internet & digital services in VI Territory

- Physical – above/below ground, undersea, fiber/wireless, etc.
- Logical – intra/inter island, organizational, etc.
Modeling and Analysis of USVI Territorial Internet Infrastructure

Goals:
• Model-based assessment of Internet & digital services in VI Territory during normal and post-hurricane conditions
• Inform efficacy/prioritization of new telecom investment
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Methodology:
• Gather available data from viNGN and other stakeholders
• Supplement physical topology data with crowd-sourced data
  – net.tagger app (https://www.cmand.org/tagger/)
Supplementing physical topology: net.tagger

- Crowd-source physical communications infrastructure data
- App publicly available for Android/iPhone – anyone can contribute
net.tagger sample tags

buried/hidden infrastructure

Infrastructure condition

wireless

power dependency
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Methodology:
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  – net.tagger app (https://www.cmand.org/tagger/)
• Supplement logical topology data with Internet measurements
  – Yarrp measurement scans hosted at UVI St. Croix and worldwide (https://www.cmand.org/yarrp/)
  – CAIDA Ark historical and new measurements (http://www.caida.org/projects/ark/)
New Ark node top be installed at UVI St. Croix (Oct 2019)
Ongoing Work: infrastructure interdependence

Effort 1 - Modeling and analysis of interdependent critical infrastructure systems

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**Electric Power Model**
- Determine optimal load shed to keep critical loads running

**Water Distribution Model**
- Identify where water services will be lost when pumps & tanks fail

**Transportation Model**
- Measure optimal supply and roadway congestion post-disaster
Our work in the USVI: several related research efforts

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How does this work help with risk and resilience?
How does this work help with risk and resilience?

CISA Strategic Risk Management Process

1. IDENTIFY
2. ANALYZE
3. PRIORITIZE
4. MANAGE

How does this work help with risk and resilience?

CISA Strategic Risk Management Process

1. Identify
   - scenarios
   - events
   - threats

2. Analyze
   - likelihoods
   - impacts

3. Prioritize
   - risks
   - average losses
   - scores

4. Manage
   - Avoid
   - Mitigate
   - Transfer
   - Retain

A Simplified View of Traditional Risk Analysis

Identify
- scenarios
- events
- threats

Assess
- likelihoods
- impacts

Evaluate
- risks
- average losses
- scores

Decide
- Avoid
- Mitigate
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A Simplified View of Traditional Risk Analysis

- You cannot predefine all threats!
- You will be surprised!

Idea #1: **Start by focusing on delivery of services, not** mitigation of hazards/threats
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**What we need to do**  
(operation)

- Electricity
- Fuels
- Transportation
- Communications
- Water & Wastewater
- Emergency response
# Idea #1: Start by focusing on delivery of services, **not** mitigation of hazards/threats

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Idea #2: **Avoid getting stuck on predefined threat scenarios.**

- Surprise Happens. Things we have not imagined.
- Tunnel vision (on the last disaster). Need to be proactive, not reactive.
How does this work help with risk and resilience?

CISA Strategic Risk Management Process

1. IDENTIFY
2. ANALYZE
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How does this work help with risk and resilience?

CISA Strategic Risk Management Process

1. IDENTIFY
   - Document national critical functions
   - Convene stakeholder groups connected by functions
   - Identify and validate scenarios of concern

2. ANALYZE

3. PRIORITIZE

4. MANAGE
How does this work help with risk and resilience?

- You cannot predefine all scenarios!
- You will be surprised!
How does this work help with risk and resilience?

CISA Strategic Risk Management Process

1. Identify
   - Document national critical functions
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   - Identify and validate scenarios of concern

2. Analyze

3. Prioritize

4. Manage

What about resilience?

- You cannot predefine all scenarios!
- You will be surprised!
Resilience is not about *what you have*, its about *what you do*!

This is a common misperception.
Think of safety as a similar concept...
Resilience is not about *what you have*,
it's about *what you do*!

This is a common misperception.
Think of safety as a similar concept...

Think of resilience as a verb, not a noun!
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resiliency
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Think of resilience as a verb, not a noun!

Our focus: Continued function of lifeline systems.

Resilience ≈ “being poised to adapt”

Emphasize active processes

   Sensing • Anticipating • Adapting • Learning

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Effort 3 - Capacity building & workforce development program

Coursework + Internship + Mentorship

I am INQUSITIVE.

I am INVOLVED.

I am INNOVATIVE.

I am READY.
Effort 3 - Capacity building & workforce development program

Coursework + Internship + Mentorship

Students learn about a diversity of topics:
• technological systems (a.k.a. built infrastructure)
• human systems (a.k.a. social infrastructure)
• environmental systems (a.k.a. natural infrastructure)
Effort 3 - Capacity building & workforce development program

Coursework + Internship + Mentorship

Students learn about a diversity of topics:
- technological systems (a.k.a. built infrastructure)
- human systems (a.k.a. social infrastructure)
- environmental systems (a.k.a. natural infrastructure)

Students intern at local organizations:
- Infrastructure operators
- Local government
- Non-government organizations
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Students reflect on their experience
• Shared experience informs multiple perspectives
• New perspectives => new insights

Students are prepared to enter the workforces as agents of innovation and change.
Our work in the USVI: several related research efforts

**Effort 1** - Modeling and analysis of interdependent critical infrastructure systems
- Energy (emphasis on electric power)
- Water (emphasis on potable storage and distribution)
- Transportation & Supply Chains
- Telecommunications

**Effort 2** - Support for development of a new Hazard Mitigation and Resilience Plan
- in partnership with UVI / VITEMA (POC: Kim Waddell, Greg Guannel)

**Effort 3** - Capacity building & workforce development program
- in partnership with UVI (POC: David Morris, Greg Guannel)
Contact Information

• Dr. David Alderson
  Director, Center for Infrastructure Defense
  Naval Postgraduate School
  831-656-1814, dlalders@nps.edu
  http://faculty.nps.edu/dlalders

• Dr. Daniel Eisenberg
  Deputy Director, Center for Infrastructure Defense
  Naval Postgraduate School
  831-656-2358, daniel.eisenberg@nps.edu
  http://faculty.nps.edu/deisenberg

• NPS Center for Infrastructure Defense
  http://www.nps.edu/cid