Operational Resilience of Water and Power Systems in the US Virgin Islands

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Center for Infrastructure Defense
Energy Academic Group
Naval Postgraduate School

INFORMS Annual Meeting, Energy and Climate II
Phoenix, AZ (Nov 2018)

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

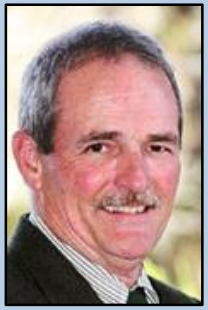
- Facilities of a graduate research university
- Faculty who work for the U.S. Navy, with clearances
- Students with fresh operational experience

FY2017:

- 65 M.S. and 15 Ph.D. programs
- 612 faculty
- 1432 resident students includes (166 international / 47 countries)
- 909 distributed learning students

NPS Center for Infrastructure Defense (CID)
Operations Research Department

David Alderson
Associate Professor, OR
Director, NPS Center for Infrastructure Defense
Ph.D., Stanford University, 2003



Gerald Brown
Distinguished Emeritus Professor, OR
Member, National Academy of Engineering
Ph.D., U.C.L.A., 1974

W. Matthew Carlyle
Professor & Chair, OR

Ph.D., Stanford University, 1997

Robert Dell
Professor, OR

Ph.D., S.U.N.Y. Buffalo, 1990

Daniel Eisenberg
Research Assistant Professor, OR

Ph.D., Arizona State University, 2018

Javier Salmerón
Associate Professor, OR

Ph.D., Universidad Politécnica (Spain), 1998

NPS Energy Academic Group (EAG)

Dan Nussbaum
Visiting Professor, OR
Chair, NPS Energy Academic Group

Ph.D., Michigan State Univ., 1971

Alan Howard
Deputy Director, NPS Energy Academic Group

MBA/MIM in International Management, 2000

Jack Templeton
Program Manager, NPS Energy Academic Group

MSM Defense Systems Analysis, NPS, 2013

What is Critical Infrastructure?

- ***Critical Infrastructure (CI)***: "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" ***--Section 1016(e) of the USA PATRIOT Act of 2001***











Critical Infrastructure Systems: NPS has a unique perspective and capability

We have been studying critical infrastructure for decades.

Problems of interest:

- Attack: Where to attack infrastructure to disrupt function?
- Defense: Where to 'harden' systems to survive attack?
- Design: How to invest limited resources (redundancy, capacity expansion, new construction) to systems perform even when 'bad things' happen (mission assurance)?
- Recovery: What to fix, in what order, how to plan?
- Resilience: for operation of critical systems

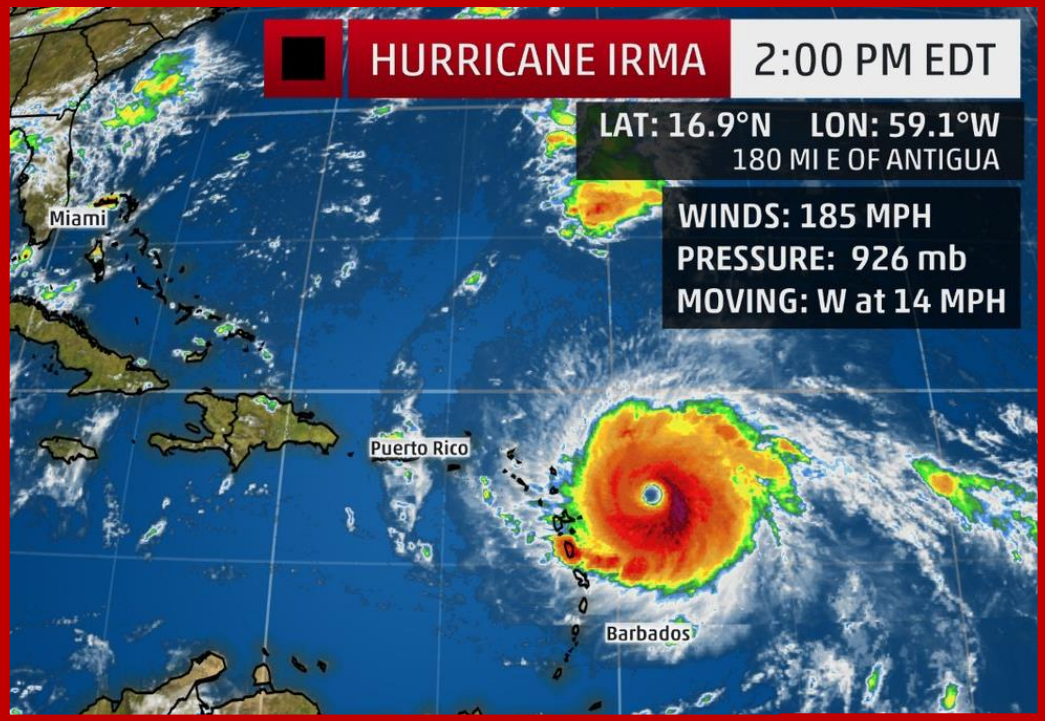
National policy for "operational resilience"

U.S. National Strategy for Homeland Security (2007)

"We will not be able to deter all terrorist threats, and it is impossible to deter or prevent natural catastrophes. We can, however, mitigate the Nation's vulnerability to acts of terrorism, other man-made threats, and natural disasters by **ensuring the structural and operational resilience** of our critical infrastructure and key resources" (p. 27)

"We must now focus on the **resilience of the system as a whole** – an approach that centers on investments that make the system better able to absorb the impact of an event without losing the capacity to function" (p.28)

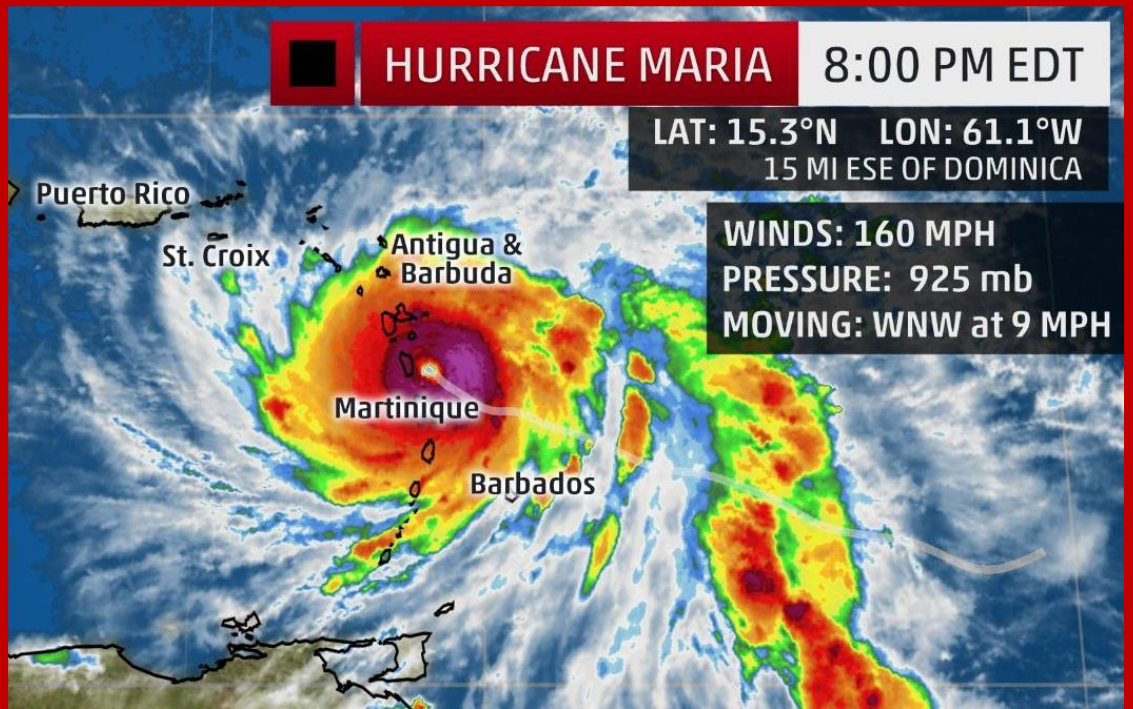
Most recently: U.S. Presidential Policy Directive (PPD)-21: Critical Infrastructure Security and Resilience, 2013.

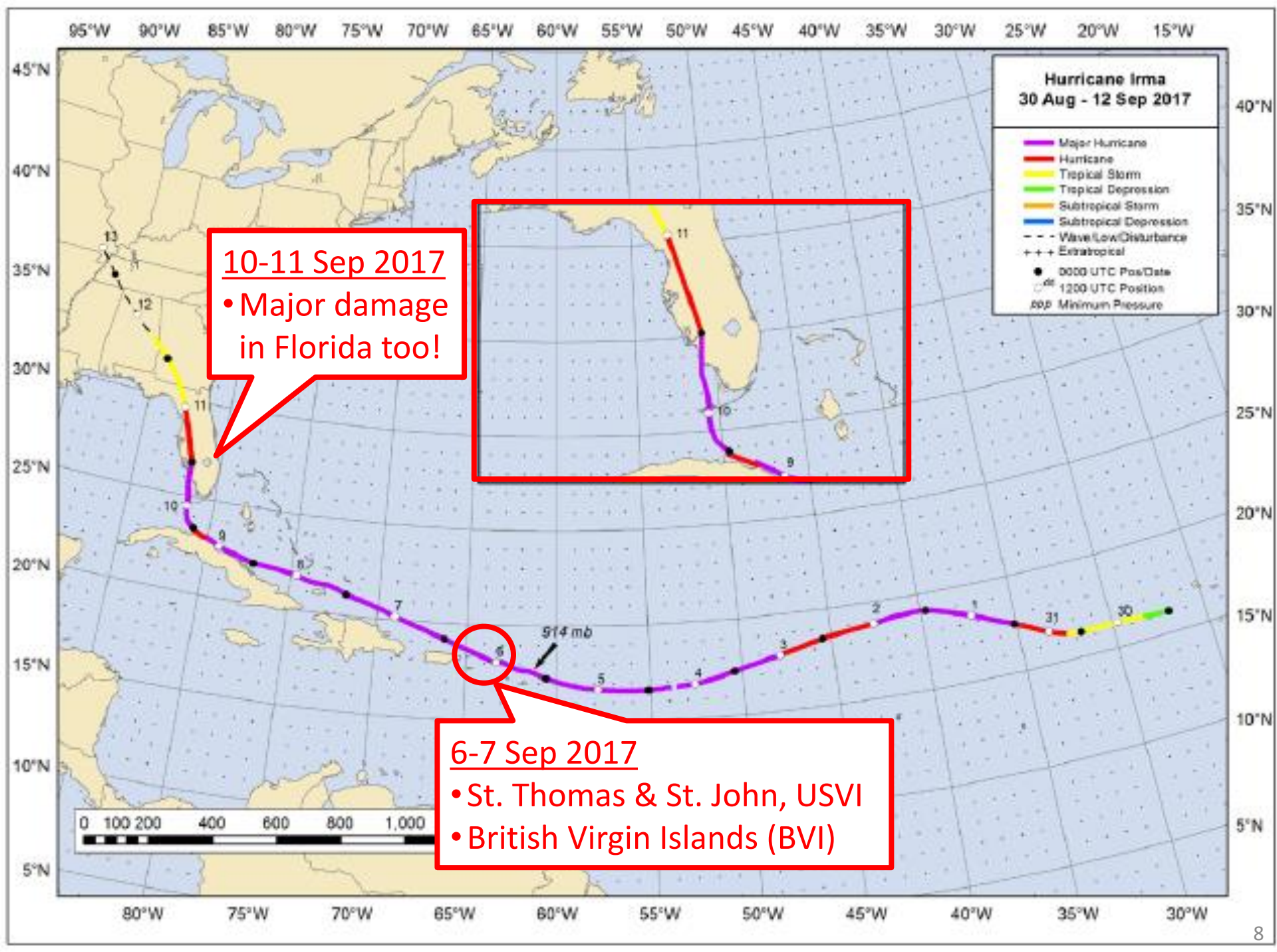


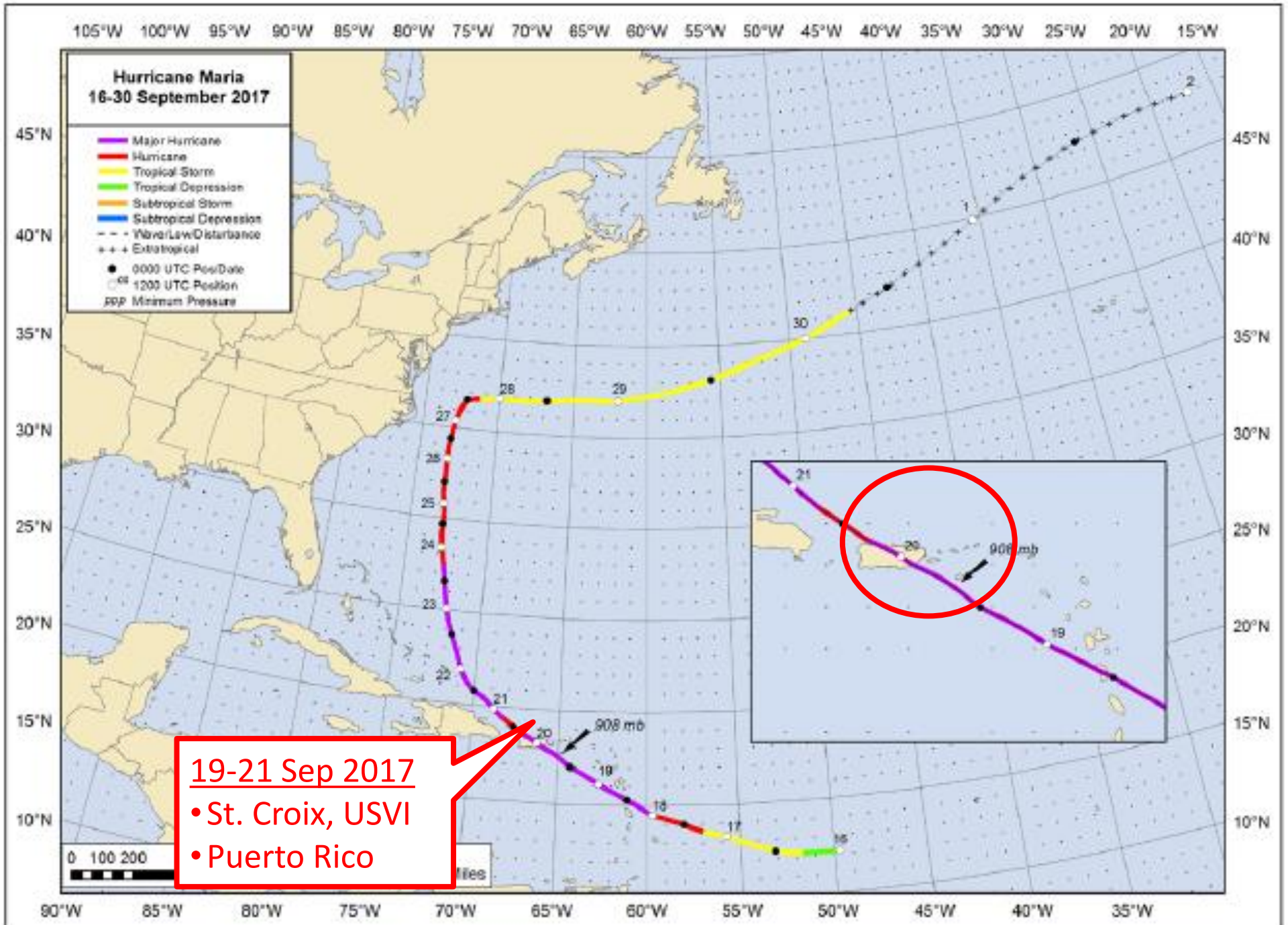
6-7 SEP 2018
Category-5 Hurricane
St. Thomas & St, John, USVI
British Virgin Islands

10-11 SEP 2018
Florida

19-21 SEP 2018
Category-5 Hurricane
St. Croix, USVI
Puerto Rico

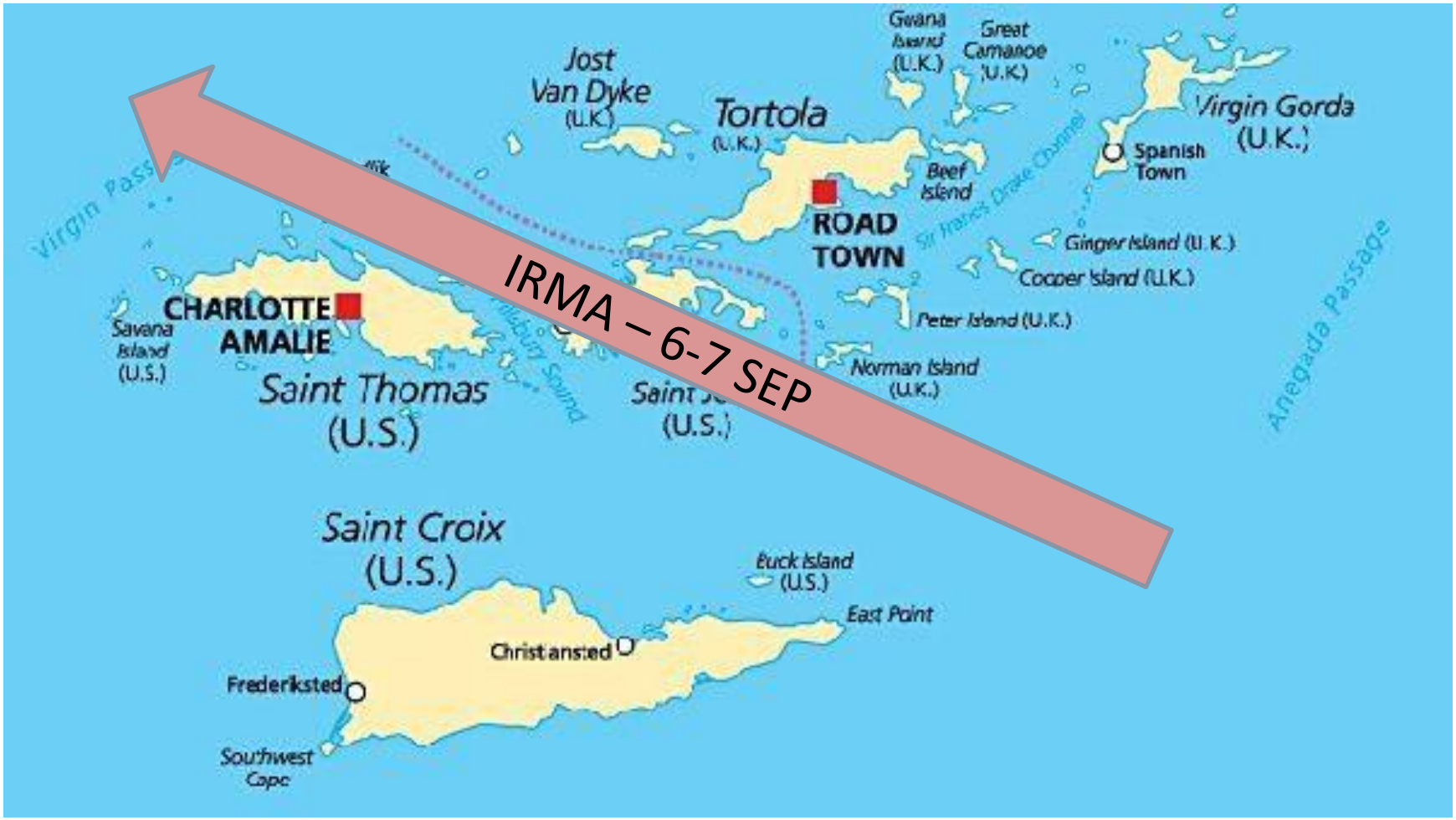



Hurricane Irma
30 Aug - 12 Sep 2017
Major Hurricane
Hurricane
Tropical Storm
Tropical Depression
Subtropical Storm
Subtropical Depression
Wave/Low/Disturbance
Extratropical
0000 UTC Pos/Date
1200 UTC Position
Minimum Pressure
914 mb
10-11 Sep 2017
• Major damage in Florida too!
6-7 Sep 2017
• St. Thomas & St. John, USVI
• British Virgin Islands (BVI)
0 100 200 400 600 800 1,000

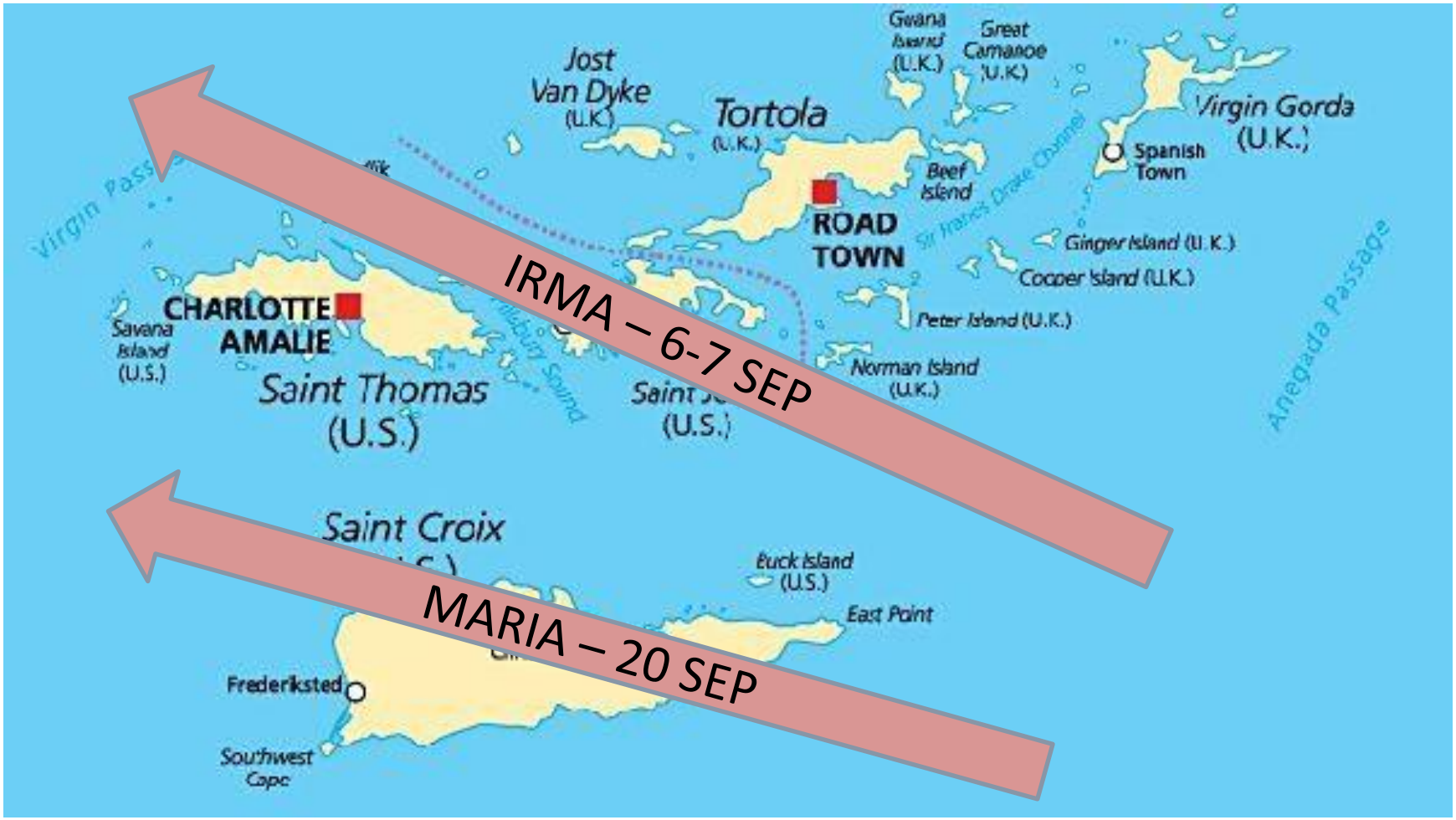

Hurricane Maria
16-30 September 2017
Major Hurricane
Hurricane
Tropical Storm
Tropical Depression
Subtropical Storm
Subtropical Depression
Wave/Low/Disturbance
Extratropical
0000 UTC Pos/Date
1200 UTC Position
ppp Minimum Pressure
908 mb
908 mb
19-21 Sep 2017
• St. Croix, USVI
• Puerto Rico

The USVI was hit by both Irma and Maria

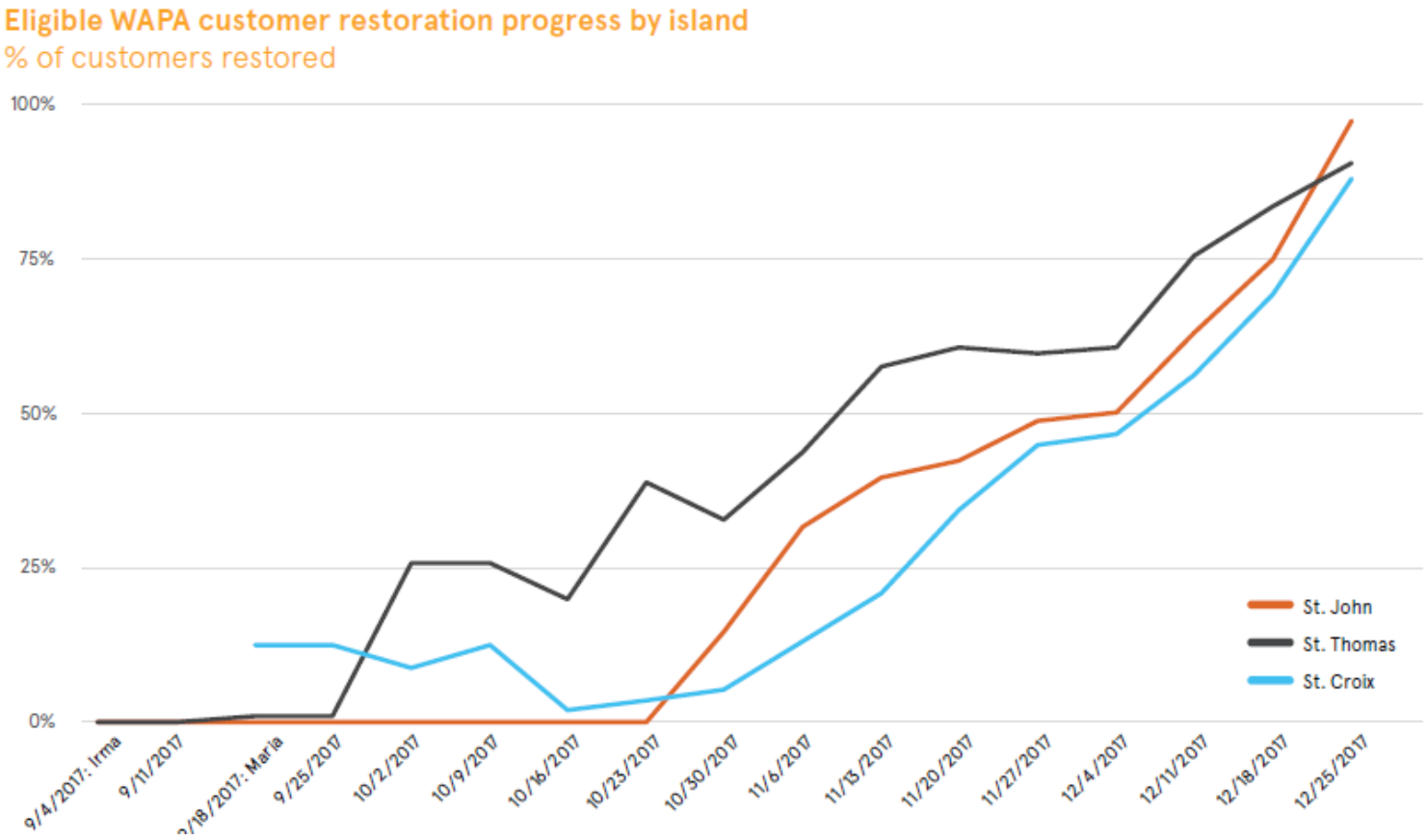
The USVI was hit by both Irma and Maria



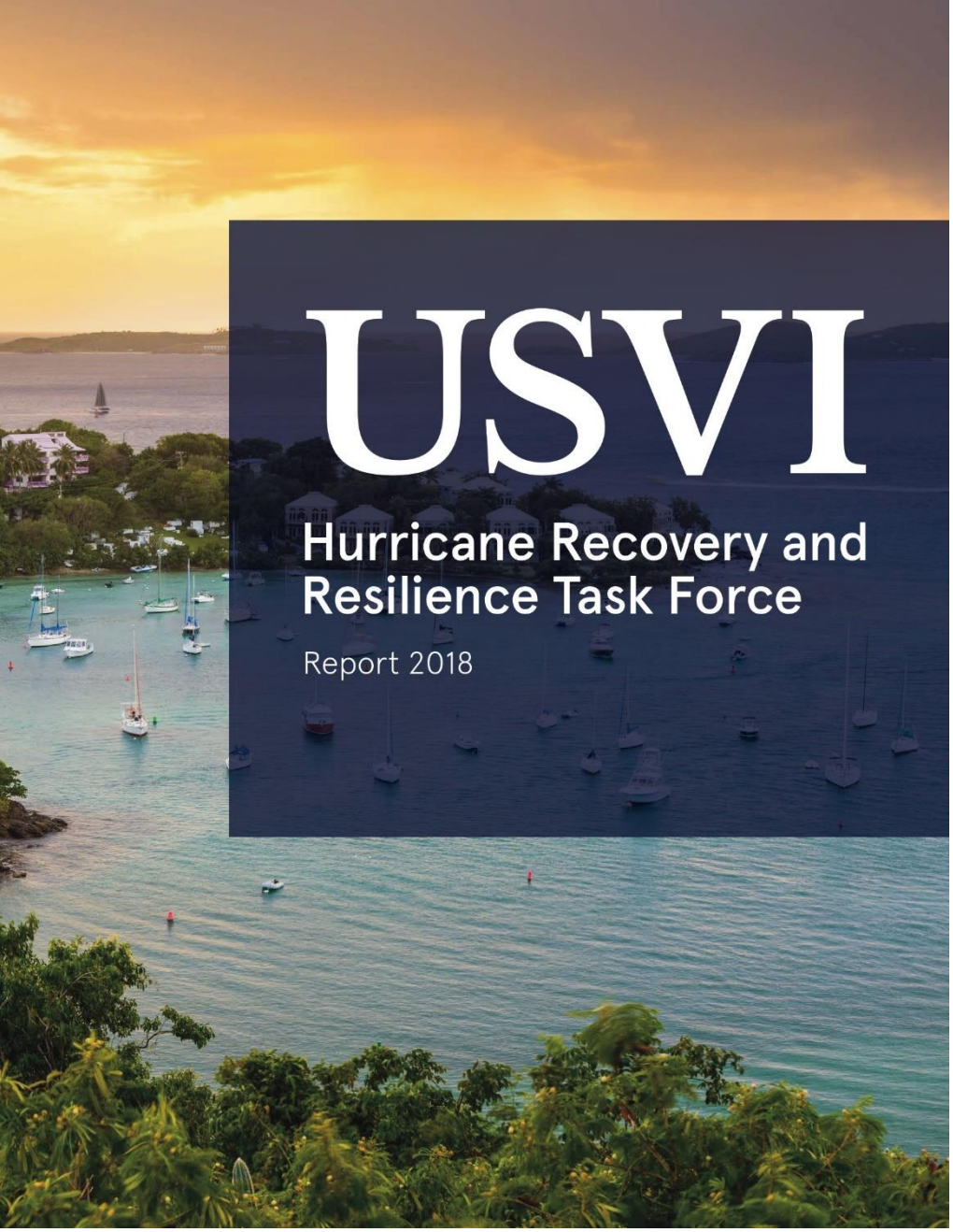
The USVI was hit by both Irma and Maria



Infrastructure Service Recovery Timeline – Electricity



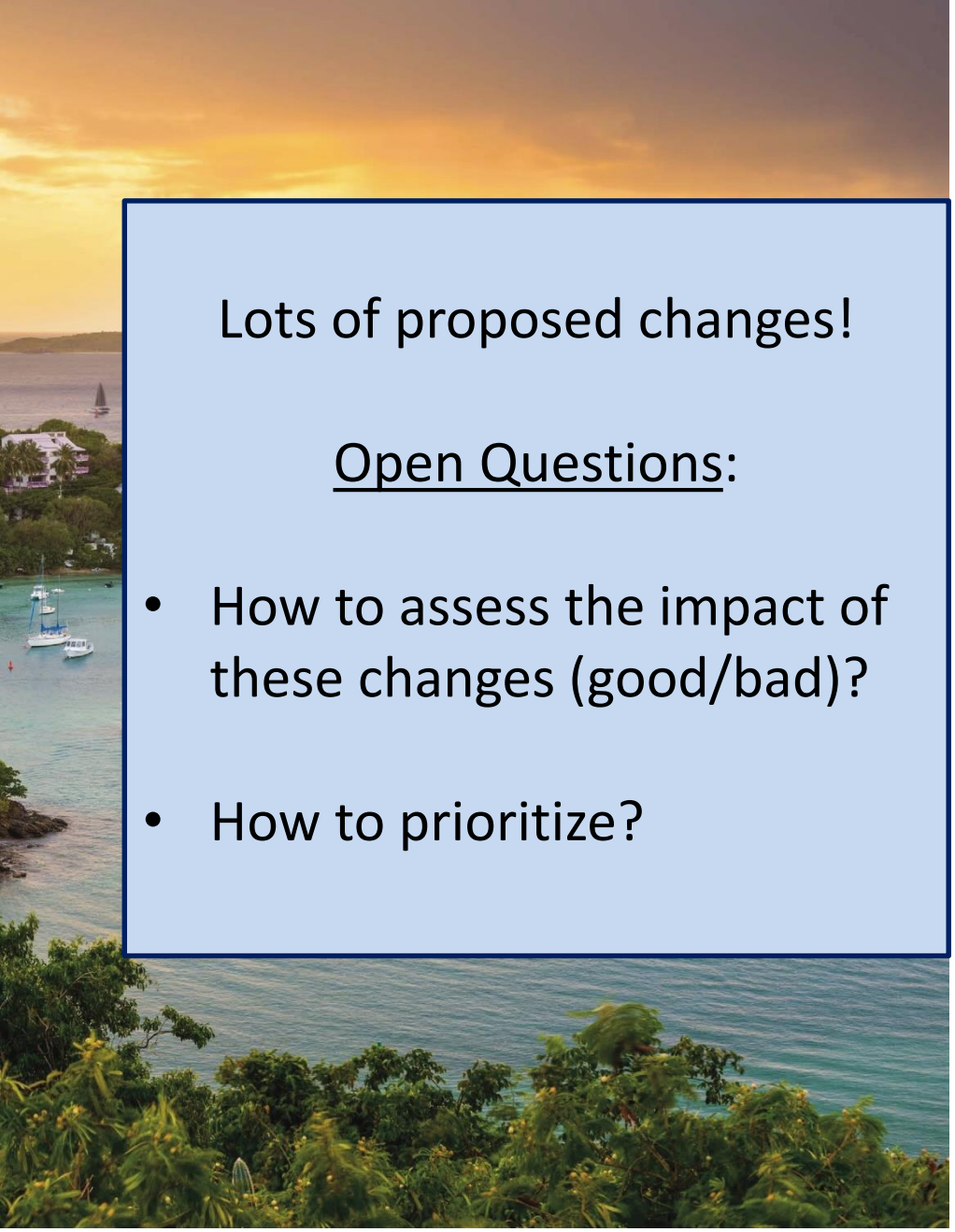
Hurricanes 1 Month 2 Months 3 Months



228 proposed initiatives across a variety of sectors:

- Climate Analysis (5)
- Energy (17)
- Private Sector Comms (14)
- Public Sector Comms (11)
- Transportation (24)
- Water (11)
- SolidWaste and Wastewater (26)
- Housing and Buildings (11)
- Health (21)
- Vulnerable Populations (12)
- Education (20)
- Economy (9)
- Non-profit, Philanthropy, and Voluntary Organizations (6)
- Government Response (41)

https://www.usvihurricanetaskforce.org/



Lots of proposed changes!

<u>Open Questions</u>:

- How to assess the impact of these changes (good/bad)?
- How to prioritize?

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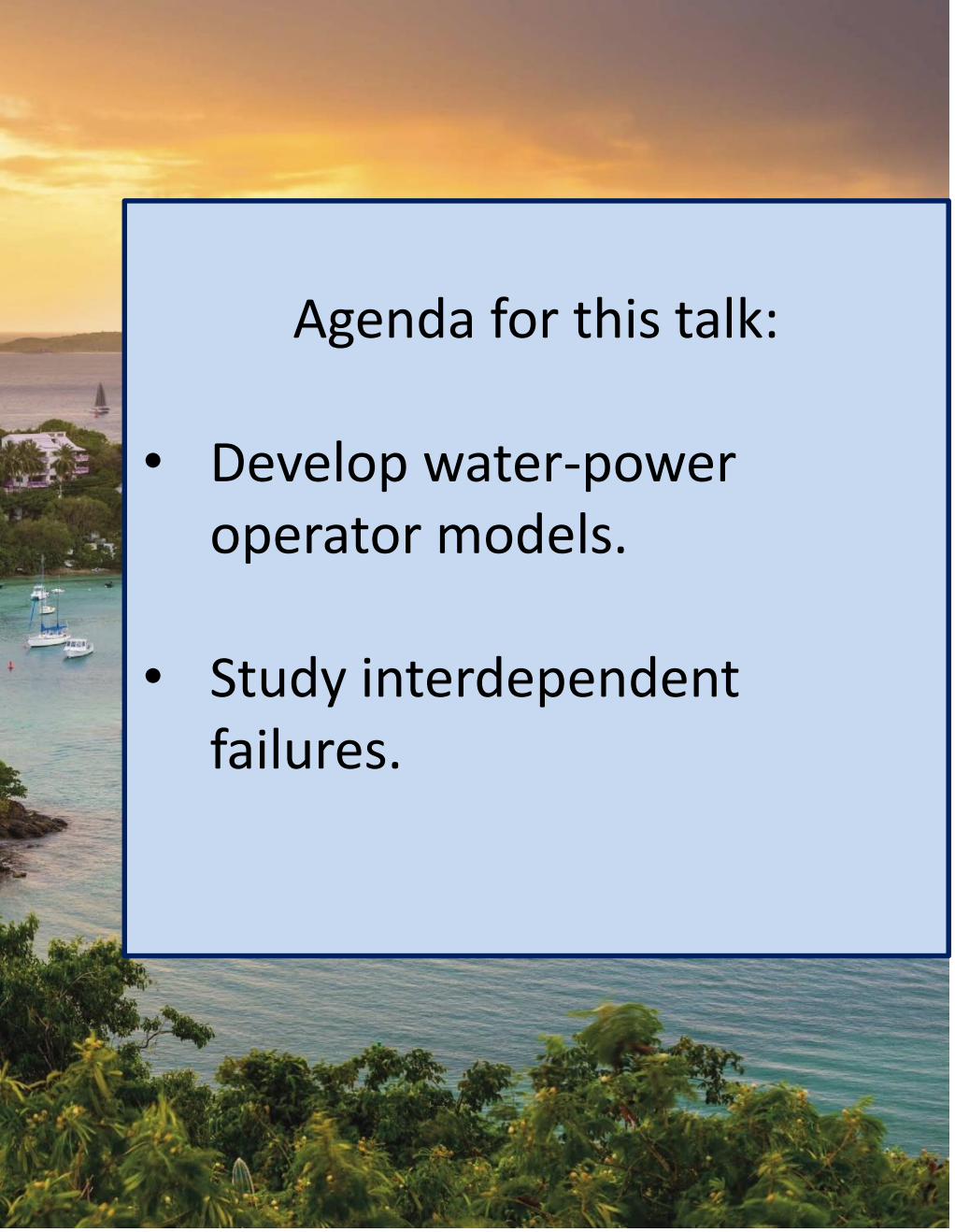

Agenda for this talk:

- Develop water-power operator models.
- Study interdependent failures.

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https://www.usvihurricanetaskforce.org/

Our research is part of a broader team effort

Our work in the USVI: several related research efforts

27 Feb 2018	Project Start (funds available)
21 Mar	remote participation in USVI Energy Roundtable
26-30 Mar	1st NPS site visit to STX, STT
11-15 Jun	2nd NPS site visit to STX, STT
14-15 Jun	UVI/VITEMA Hazard Mitigation Workshop
21 Sep	MS Thesis by LCDR Brendan Bunn
20 Oct	Technical report (final draft)
22-26 Oct	3rd NPS site visit to STX, STJ, STT

- Bunn BB, 2018, **"An Operational Model of Interdependent Water and Power Distribution Infrastructure Systems,"** M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA, September 2018.
- Alderson DL, Bunn BB, Eisenberg DA, Howard AH, Nussbaum DE, Templeton JC, **"Interdependent Infrastructure Resilience in the U.S. Virgin Islands: Preliminary Assessment,"** NPS Technical Report, Naval Postgraduate School, Monterey, CA, October 2018 (forthcoming).

Developing Water-Power Operator Models for the USVI

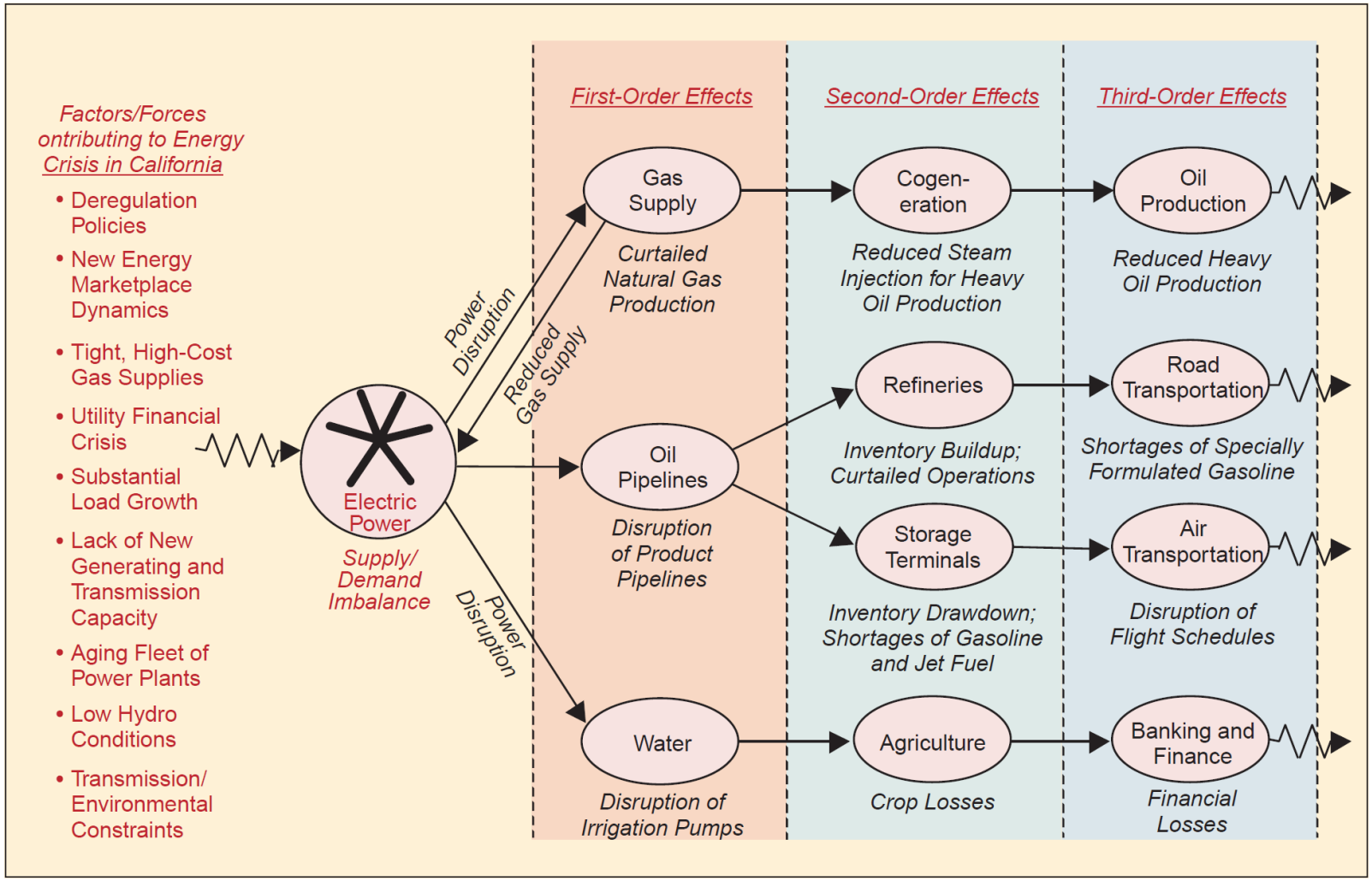
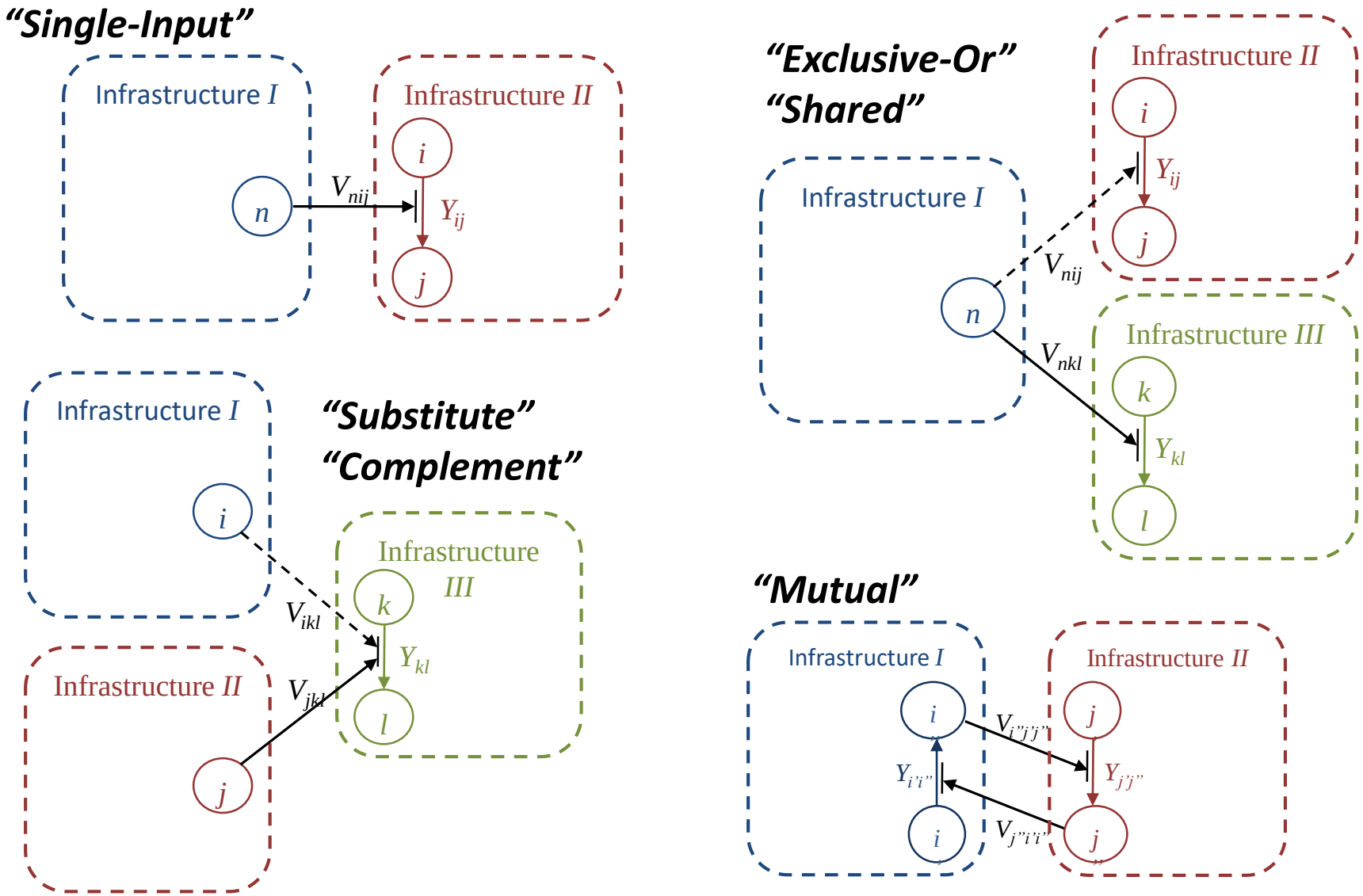


Figure 4. *Examples of nth-order interdependencies and effects.*

Rinaldi, Steven M., James P. Peerenboom, and Terrence K. Kelly. "Identifying, understanding, and analyzing critical infrastructure interdependencies." *IEEE Control Systems* 21, no. 6 (2001): 11-25.

Developing Water-Power Operator Models for the USVI



CDR Cory Dixon, "Assessing Vulnerabilities in Interdependent Infrastructures Using Attacker-Defender Models," M.S. Thesis, NPS, September 2011.

Developing Water-Power Operator Models for the USVI

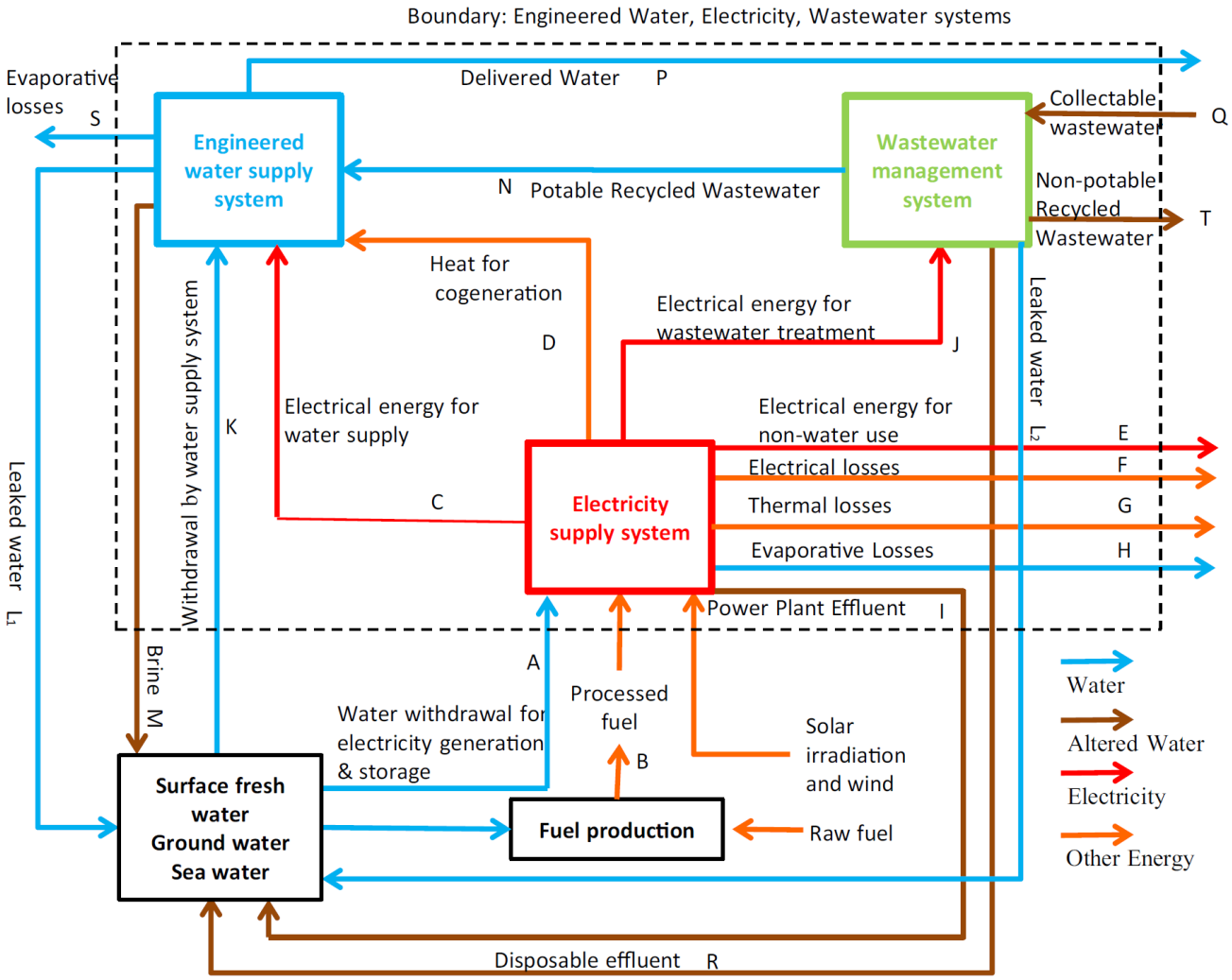
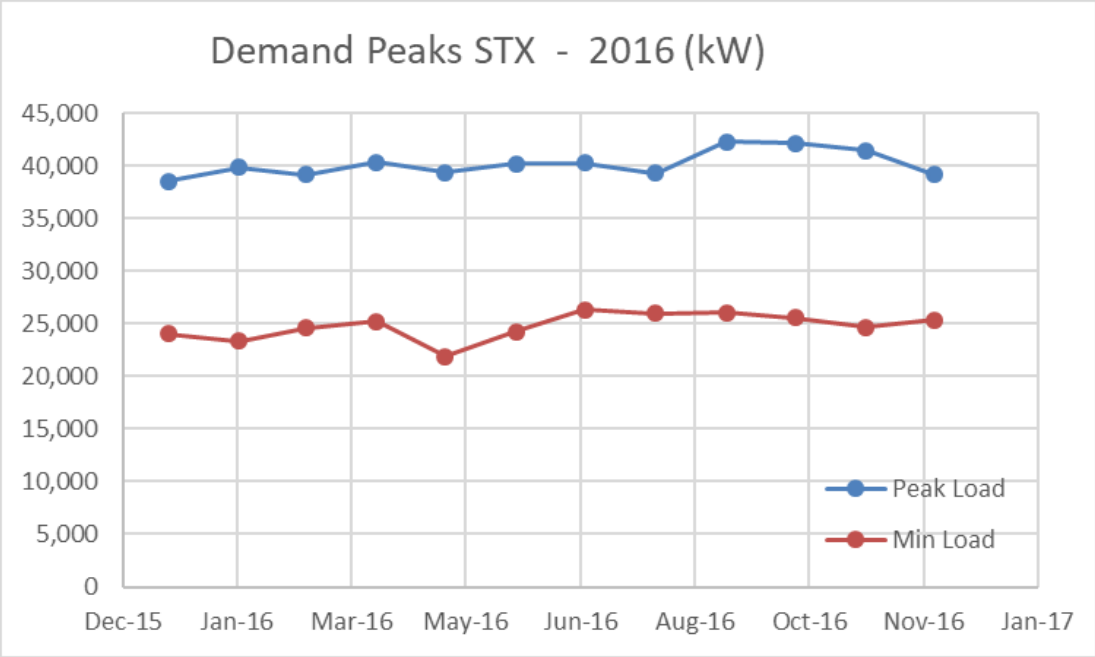


Fig. 1. System context diagram for combined electricity, water and wastewater systems.

Lubega, William N., and Amro M. Farid. "Quantitative engineering systems modeling and analysis of the energy–water nexus." *Applied Energy* 135 (2014): 142-157.

Generation – Oversized and Inefficient

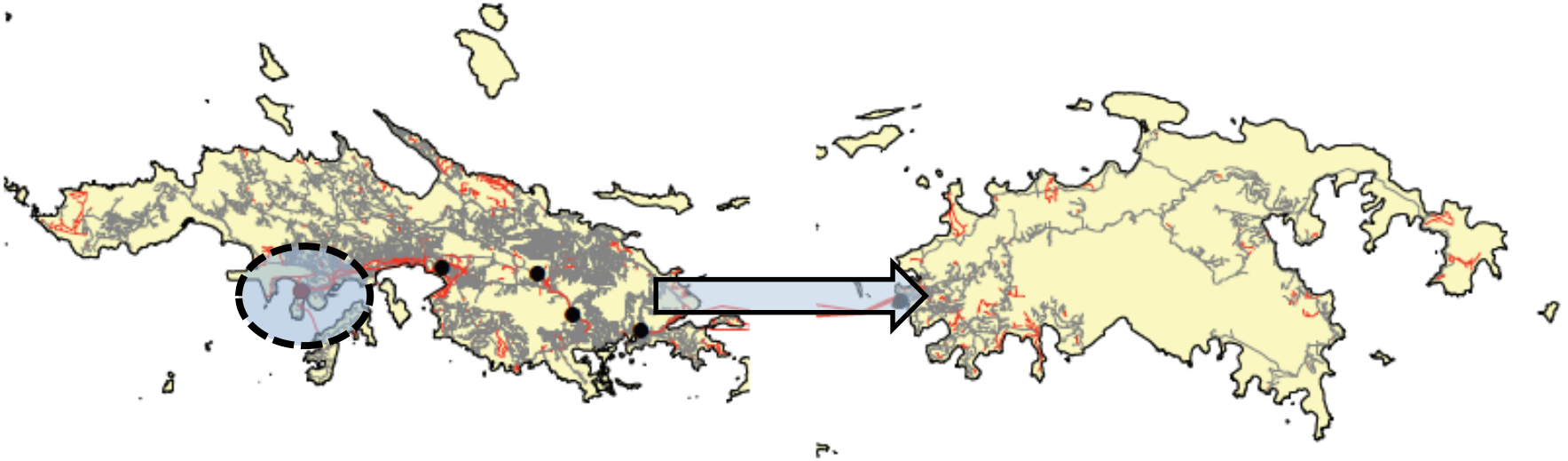


Gas Turbine Generators STX Power System			
Unit	Fuel Type	Capacity (MW)	Unit Type
10	#2 Fuel Oil	10	Worthington STG
11	#2 Fuel Oil	19.1	GE STG
16	Dual (#2 or LPG)	20.9	GE MS5001P CT
17	Dual (#2 or LPG)	21.9	Alstom
19	Dual (#2 or LPG)	22.5	GE5001
20	Dual (#2 or LPG)	22.5	GE5001

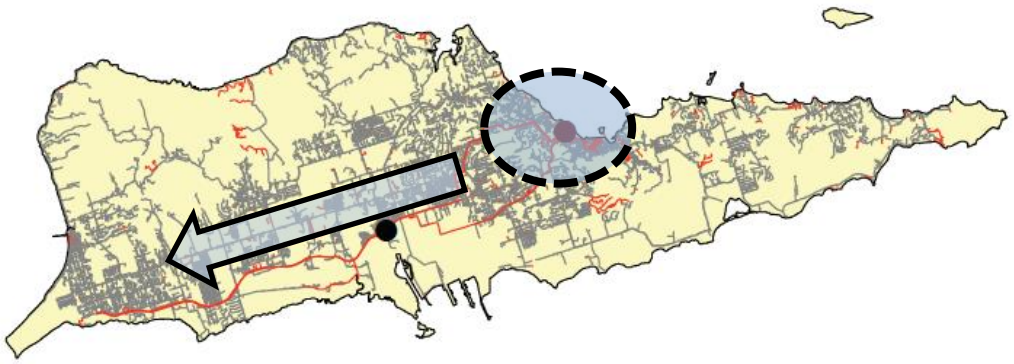
Blackstart Emergency Generators			
Unit	Fuel Type	Capacity (MW)	Unit Type
--	#2 Fuel Oil	0.75	GE6F09802

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

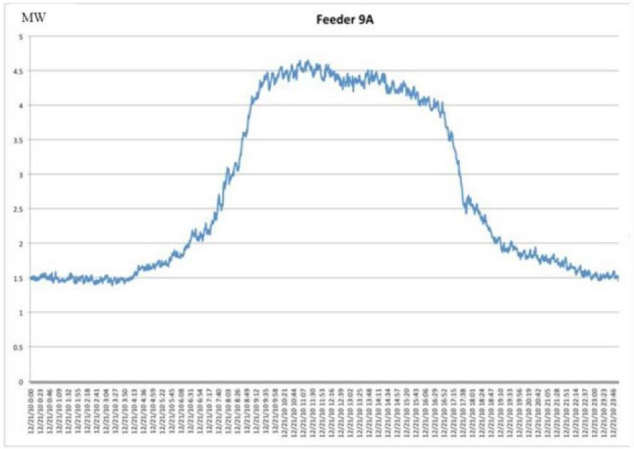
Transmission & Distribution –
Single Generation Plant Leaves Communities Vulnerable



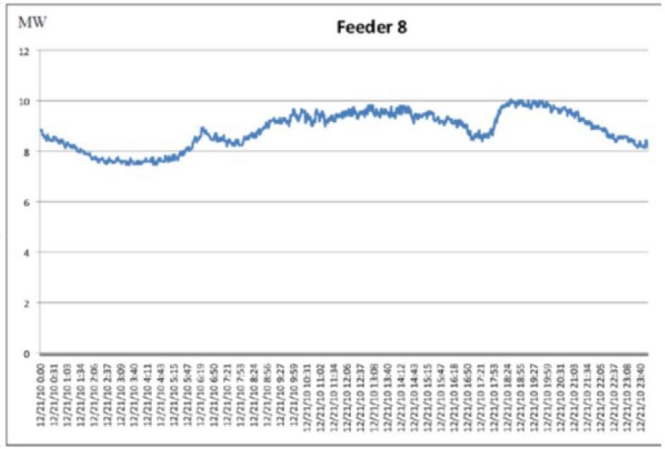
- Centralized electricity Production
- Aging generation, transmission, and distribution infrastructure



Critical Loads – (Mis)match with Community Needs

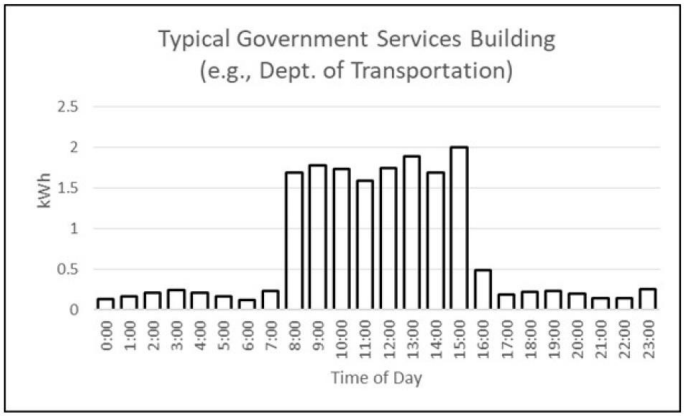


(A)

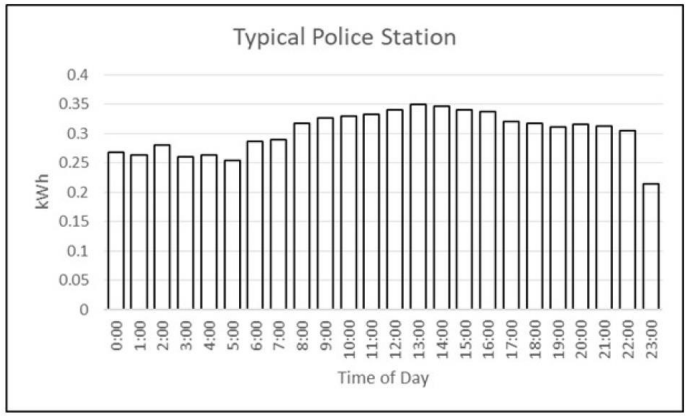


(B)

- Community industrial / commercial and residential loads have regular characteristics



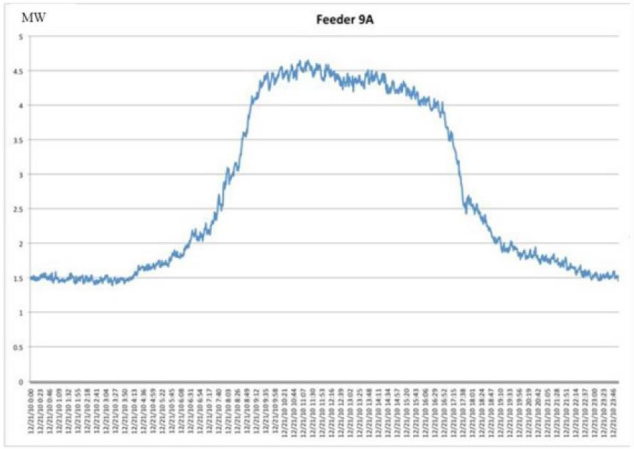
(A)



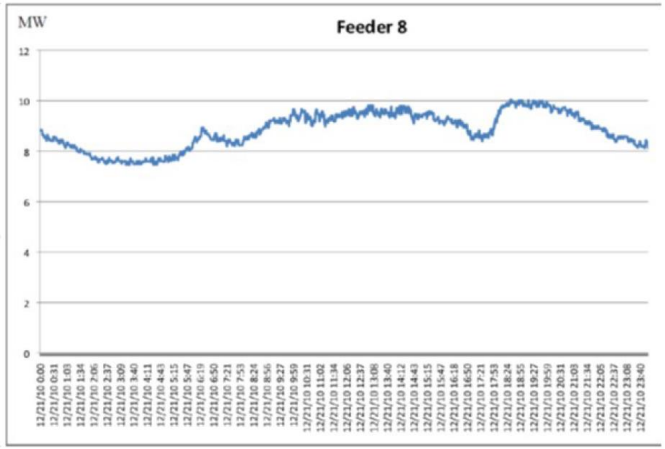
(B)

- Some critical loads match community needs

Critical Loads – (Mis)match with Community Needs



(A)



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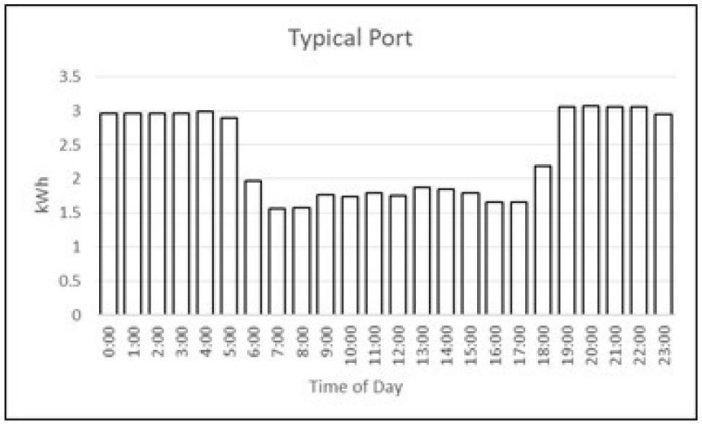
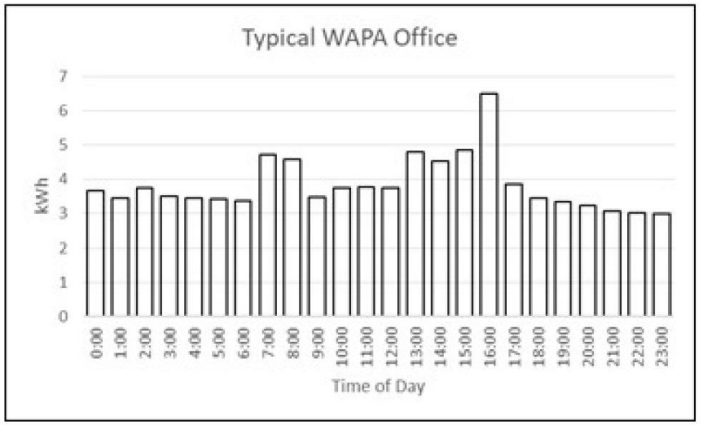


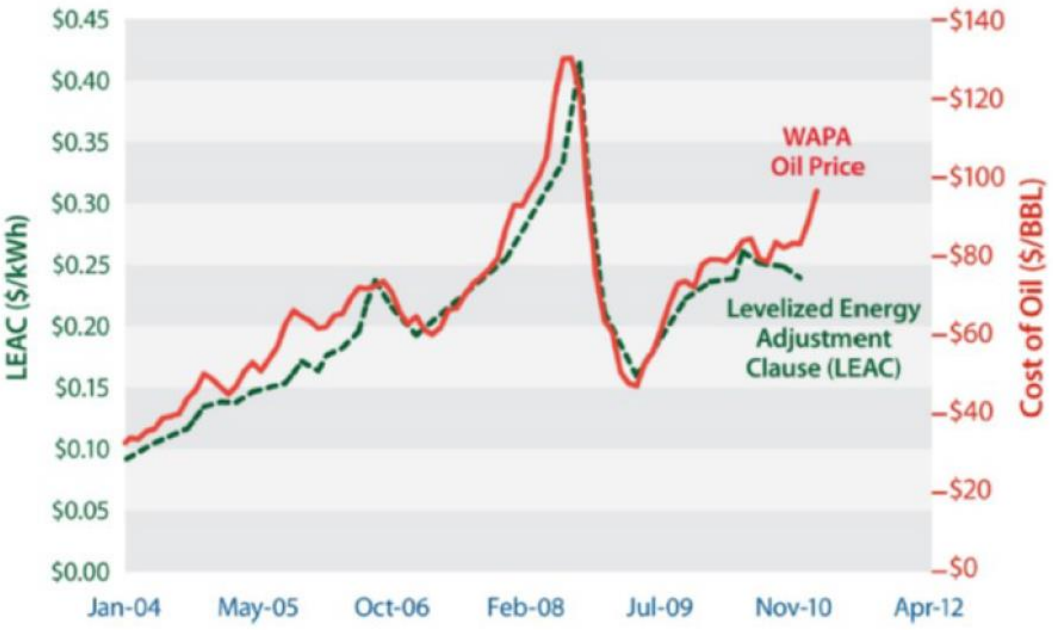
(A)



(C)

- Some critical loads do not match community needs

Economics – Volatile and Expensive Electricity Prices

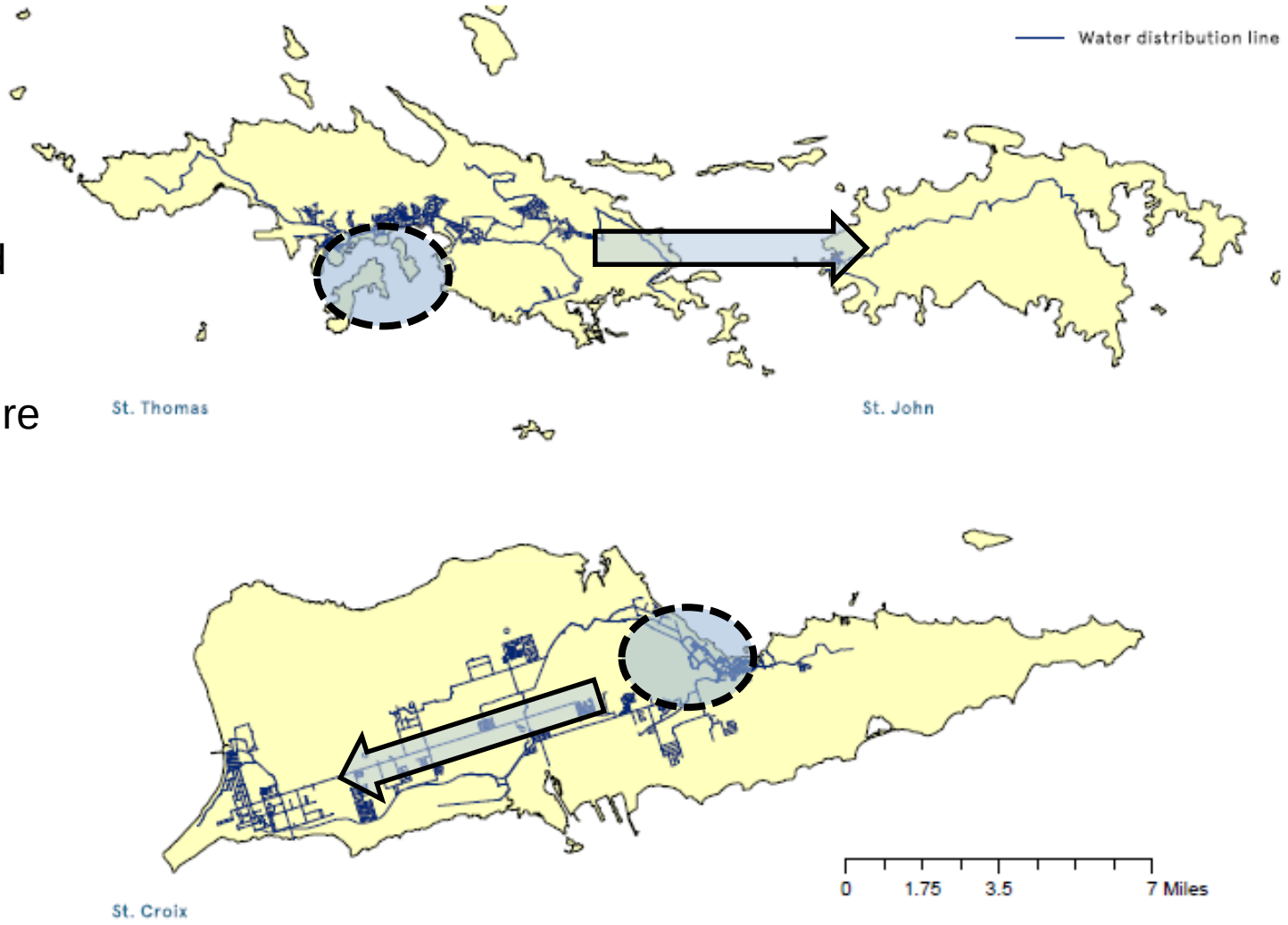


- Imported fuels are expensive and the price is volatile
- Customer electricity prices are remarkably high leading (~$0.40 per kWh).
- Defections are common

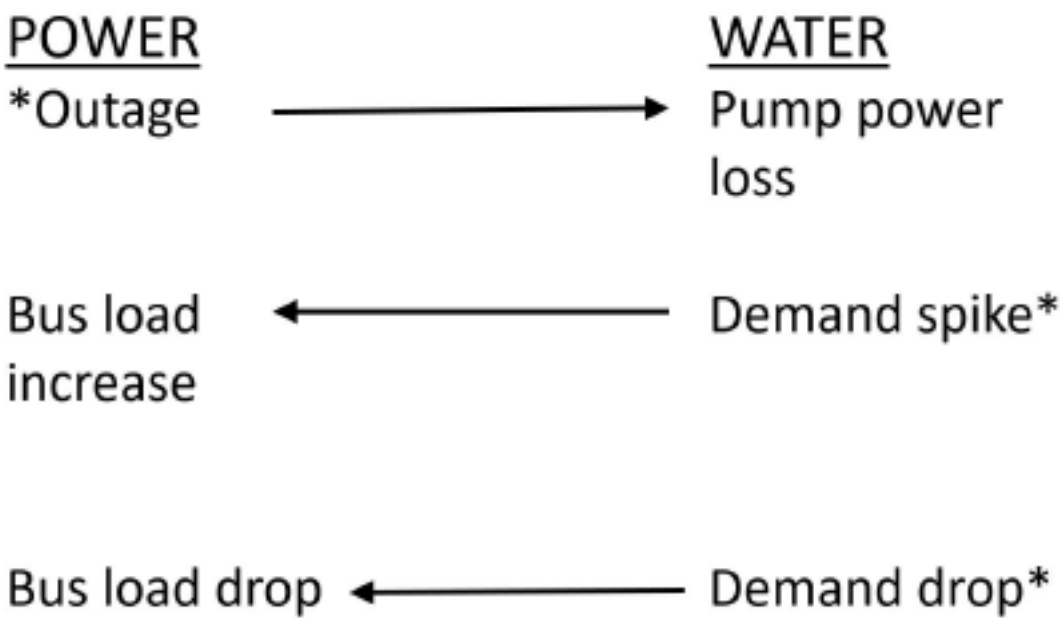
	2018 (ending 10/01)		2017		2016	
Revenues (in thousands)	$	% Total	$	% Total	$	% Total
Levelized Energy Adjustment Clause (LEAC)	129,668	57	114,562	58	135,799	61
All Other (incl. sales and surcharges)	95,927	43	83,523	42	88,450	39
Total	225,595	--	198,085	--	224,249	--

Water Distribution – Unfortunately Similar Issues

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



Interdependent Operations and Failures



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

Bunn BB, 2018, **"An Operational Model of Interdependent Water and Power Distribution Infrastructure Systems,"** M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA, September 2018.

Developing Water-Power Operator Models for the USVI

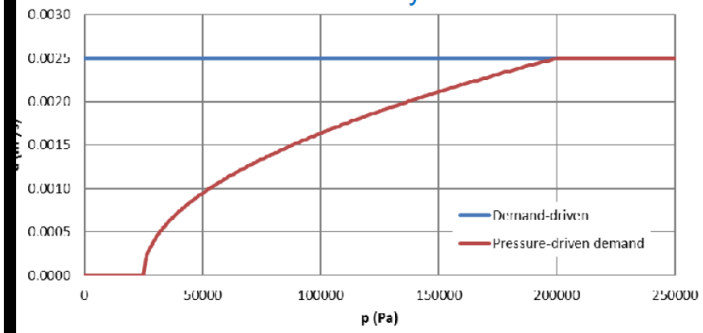
Simulation engines

Sandia National Laboratories

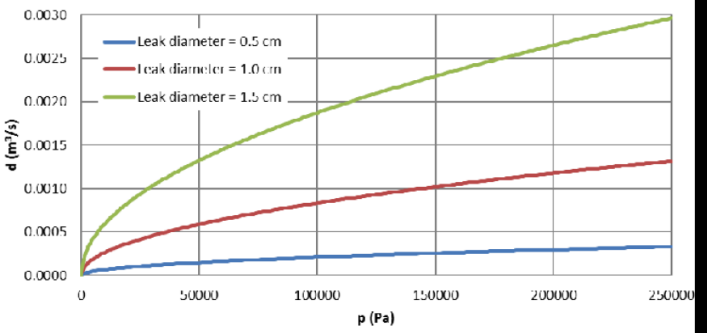
- WNTR includes two simulation options:

	DD Hydraulics	PDD Hydraulics	Water quality	Leaks	Network options	Simulation options	Control options	Start/Stop
EpanetSimulator	✓		✓	✓ Emitters	✓	✓	✓	
WNTRSimulator	✓	✓		✓	Almost all	Almost all	✓ plus relative conditions	✓

DD and PDD hydraulics



Leak model



$$d = \begin{cases} 0 & p \le P_0 \\ D_f\left(\frac{p-P_0}{P_f-P_0}\right)^{\frac{1}{2}} & P_0 \le p \le P_f \\ D^f & p \ge P_f \end{cases}$$

$$d_{leak} = C_d A p^{\alpha} \sqrt{\frac{2}{\rho}}$$

9

Klise et al., Using WNTR to Model Water Distribution System Resilience. (2017)

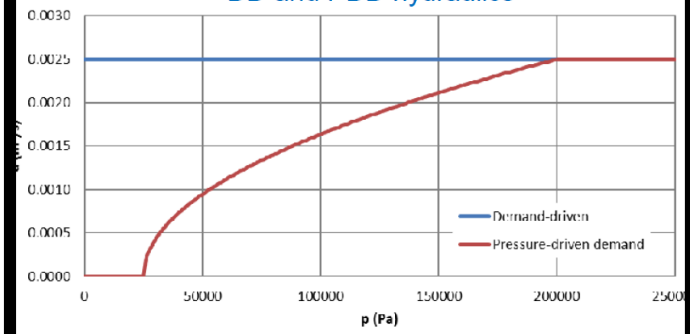
Developing Water-Power Operator Models for the USVI

Simulation engines

- WNTR includes two simulation opt

	DD Hydraulics	PDD Hydraulics	Water quality
EpanetSimulator	✓		✓
WNTRSimulator	✓	✓	

DD and PDD hydraulics



$$d = \begin{cases} 0 & p \le P_0 \\ D_f\left(\frac{p-P_0}{P_f-P_0}\right)^{\frac{1}{2}} & P_0 \le p \le P_f \\ D^f & p \ge P_f \end{cases}$$

Approved for public release. Distribution is unlimited.

ASSESSING THE OPERATIONAL RESILIENCE OF ELECTRICAL DISTRIBUTION SYSTEMS

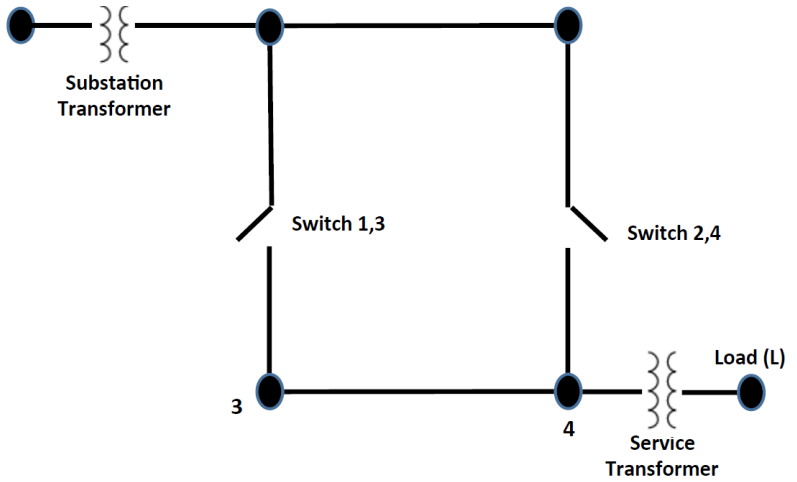
Clark Petri
Lieutenant Commander, United States Navy
B.S., Oregon State University, 2005

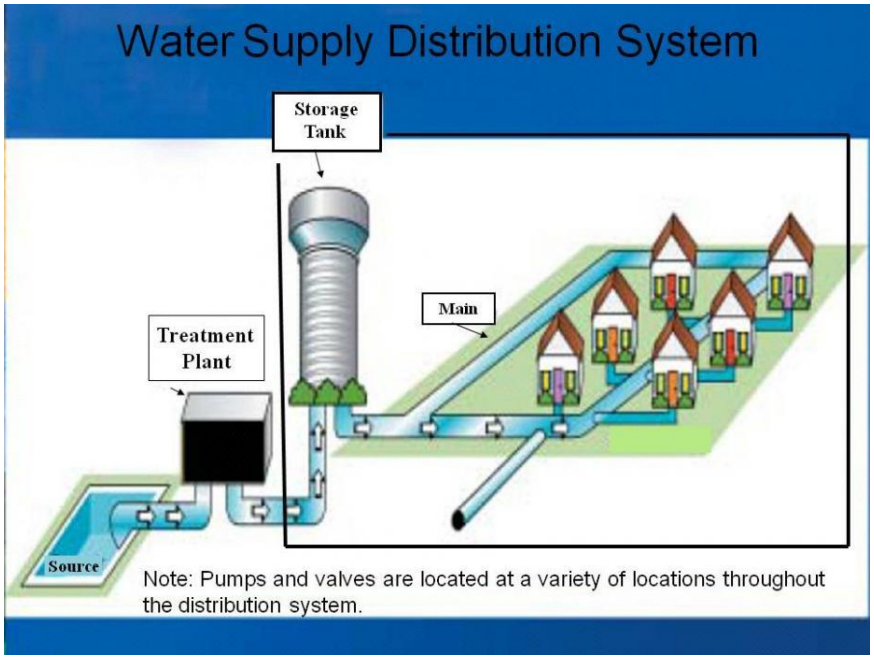
Submitted in partial fulfillment of the
requirements for the degree of

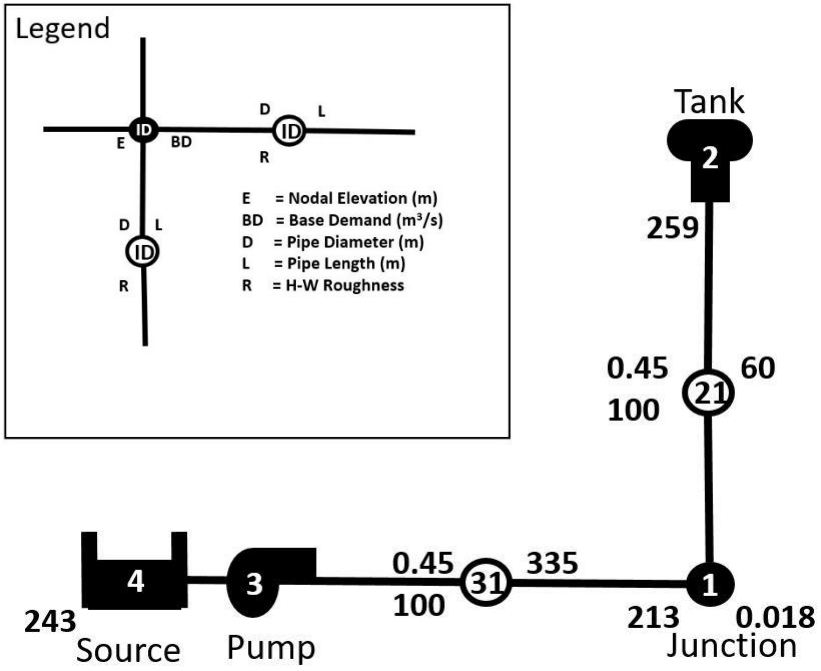
MASTER OF SCIENCE IN OPERATIONS RESEARCH

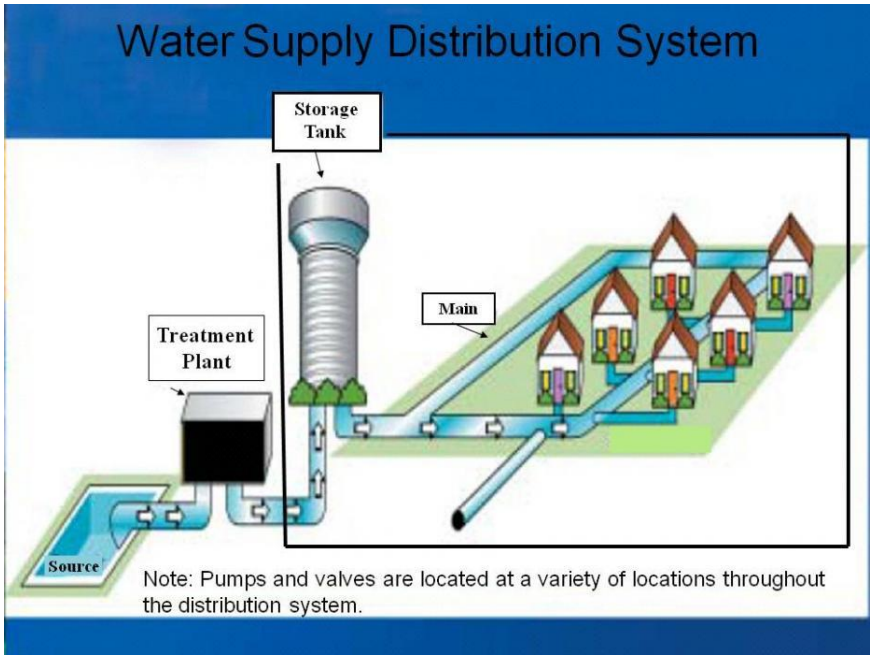
from the

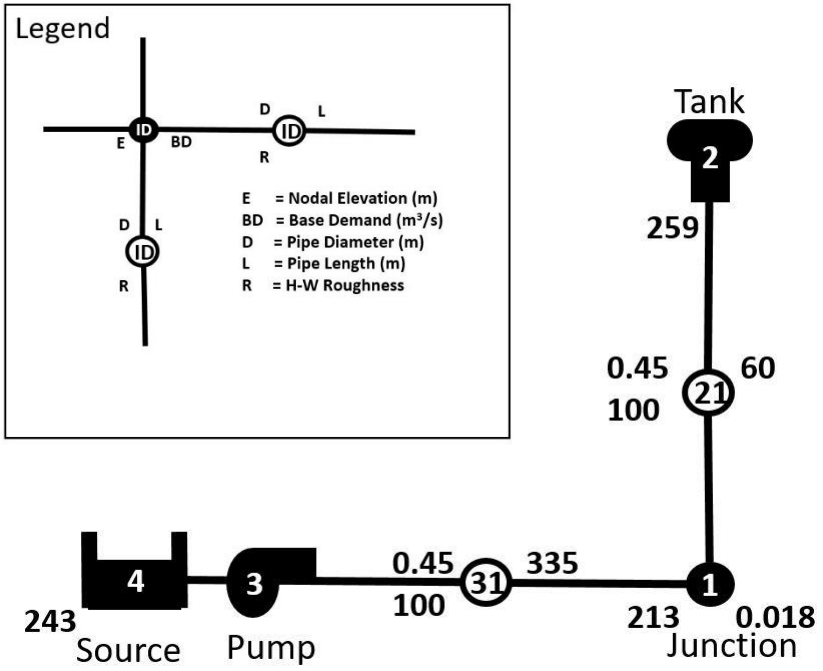
NAVAL POSTGRADUATE SCHOOL
September 2017

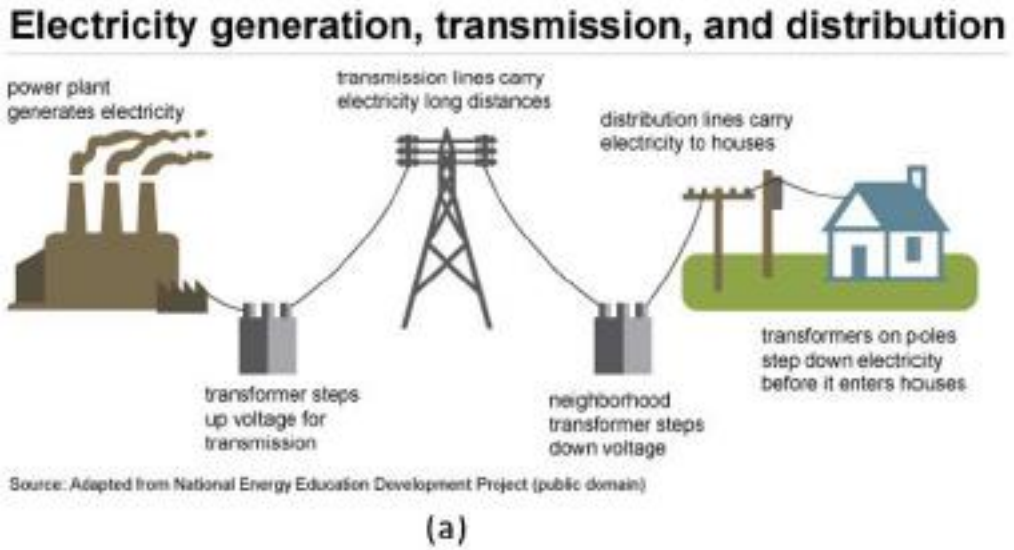


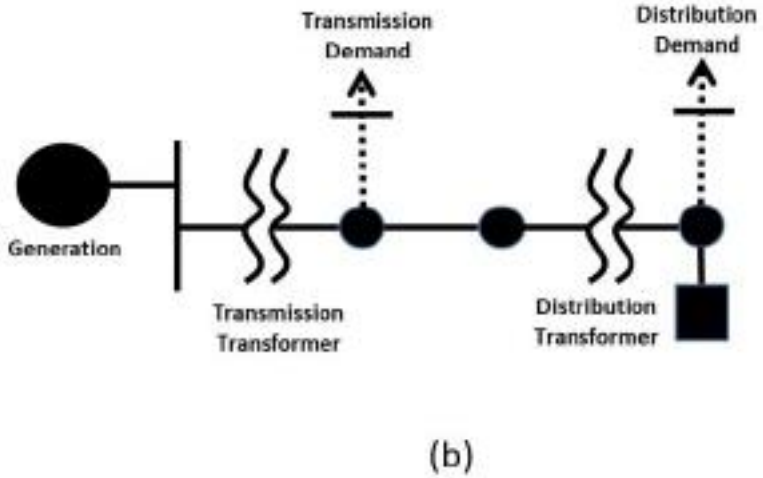

Water Supply Distribution System
Storage Tank
Treatment Plant
Main
Source
Note: Pumps and valves are located at a variety of locations throughout the distribution system.

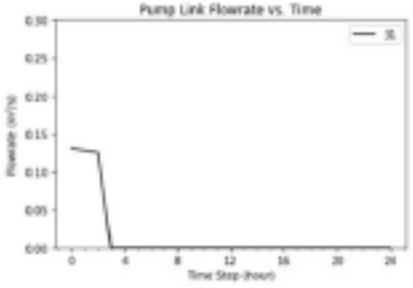

Legend
ID
E
BD
D
L
R
E = Nodal Elevation (m)
BD = Base Demand (m³/s)
D = Pipe Diameter (m)
L = Pipe Length (m)
R = H-W Roughness
Tank
2
259
0.45
100
60
21
4
3
0.45
100
335
31
1
243
Source
Pump
213
0.018
Junction

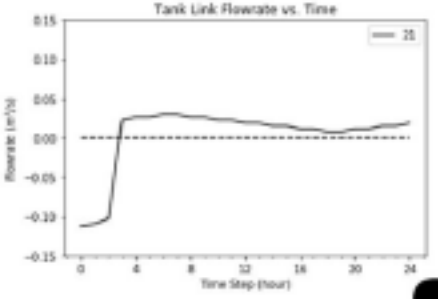

Water Supply Distribution System
Storage Tank
Treatment Plant
Main
Source
Note: Pumps and valves are located at a variety of locations throughout the distribution system.

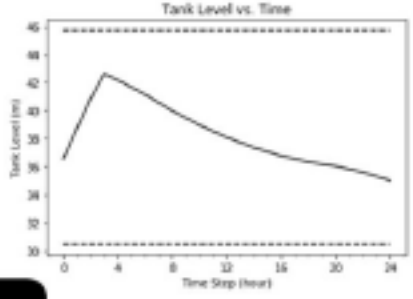

Legend
E = Nodal Elevation (m)
BD = Base Demand (m³/s)
D = Pipe Diameter (m)
L = Pipe Length (m)
R = H-W Roughness
Tank
2
259
0.45
100
60
21
4
3
0.45
100
31
335
1
243
Source
Pump
213
0.018
Junction


Electricity generation, transmission, and distribution
power plant generates electricity
transmission lines carry electricity long distances
distribution lines carry electricity to houses
transformer steps up voltage for transmission
neighborhood transformer steps down voltage
transformers on poles step down electricity before it enters houses
Source: Adapted from National Energy Education Development Project (public domain)
(a)

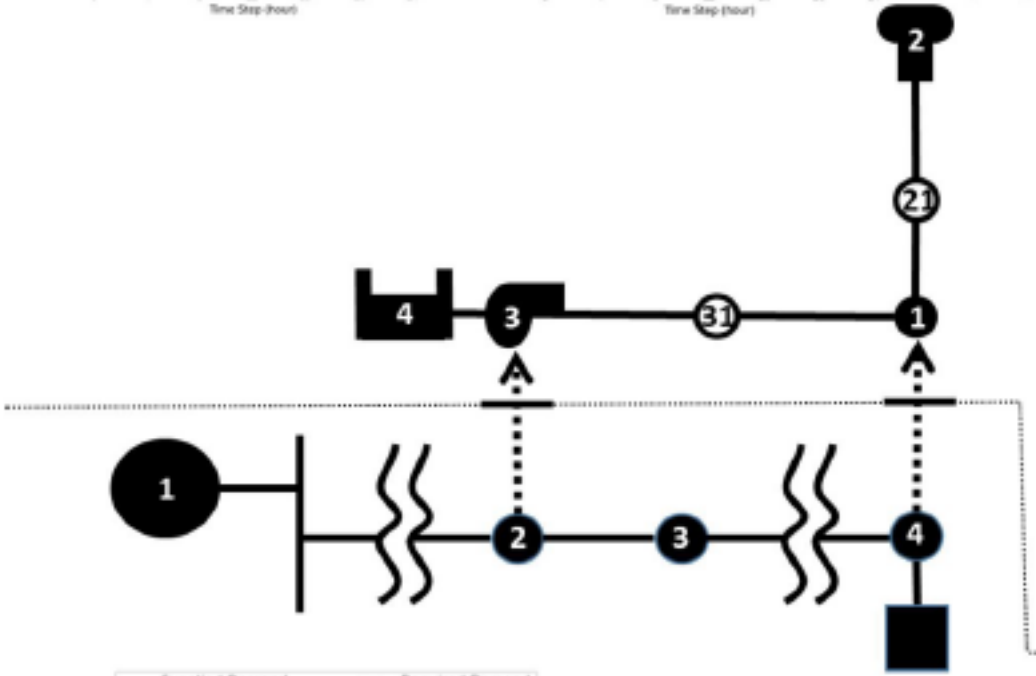

Transmission Demand
Distribution Demand
Generation
Transmission Transformer
Distribution Transformer
(b)

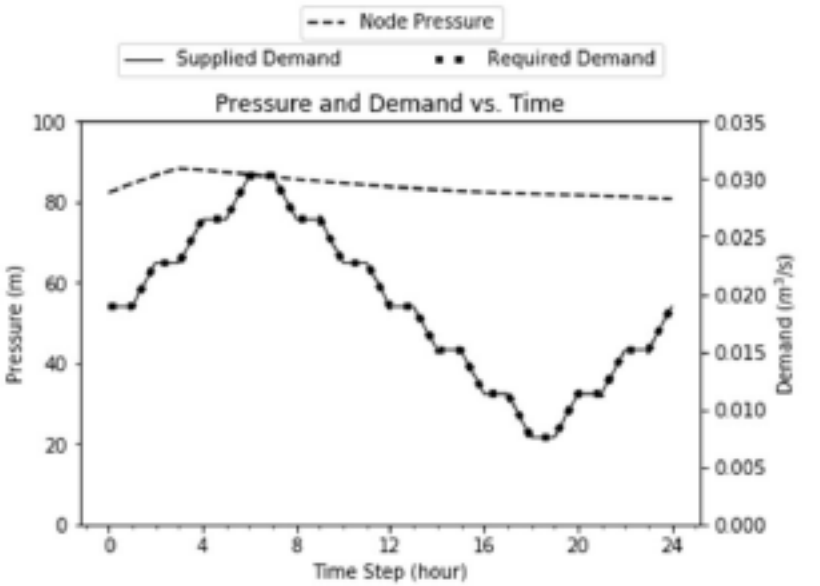


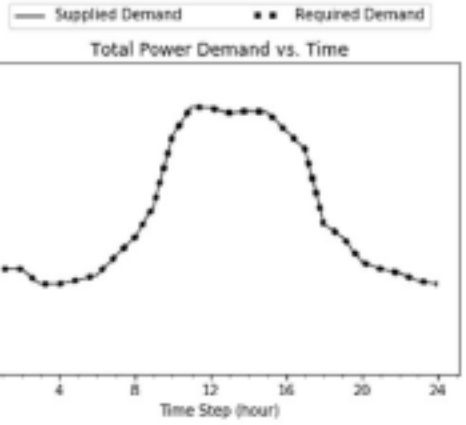


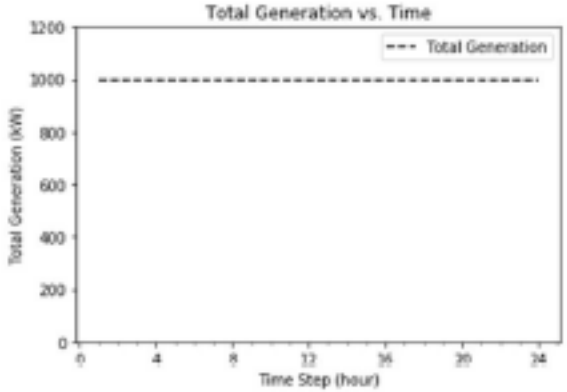


Water System

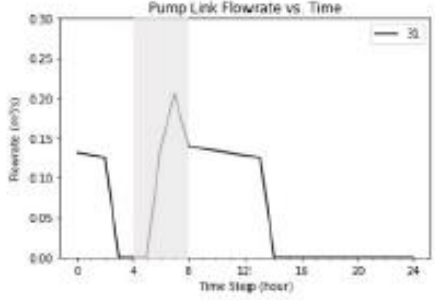


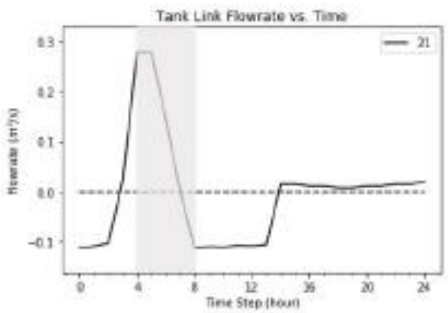


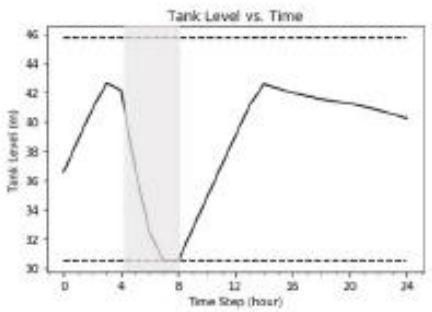


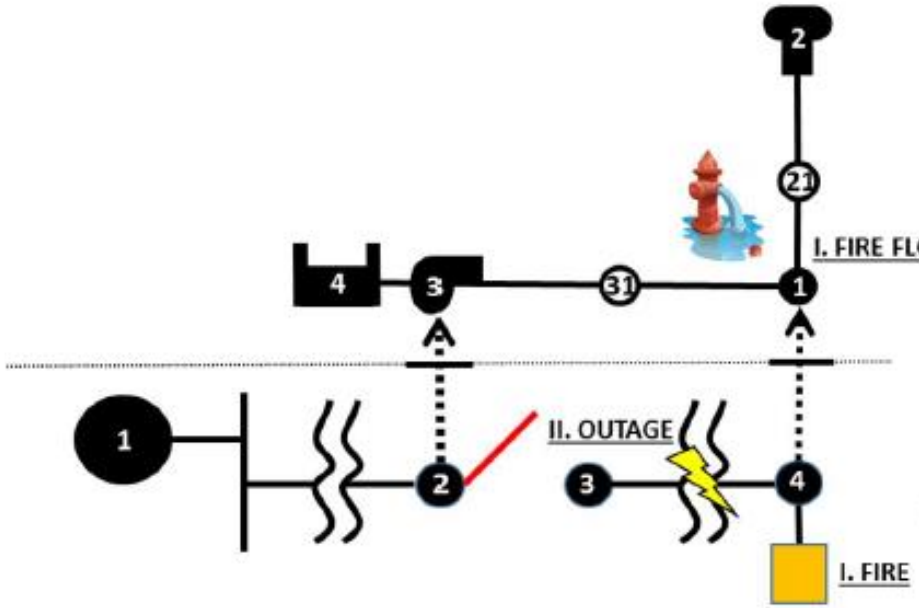


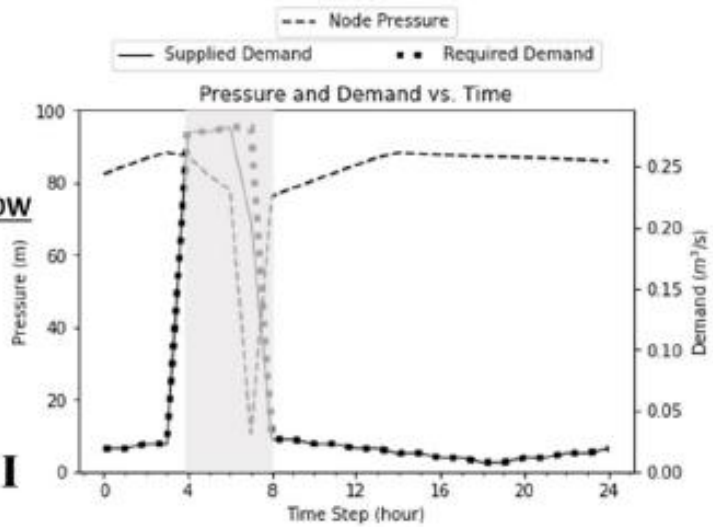
Power System

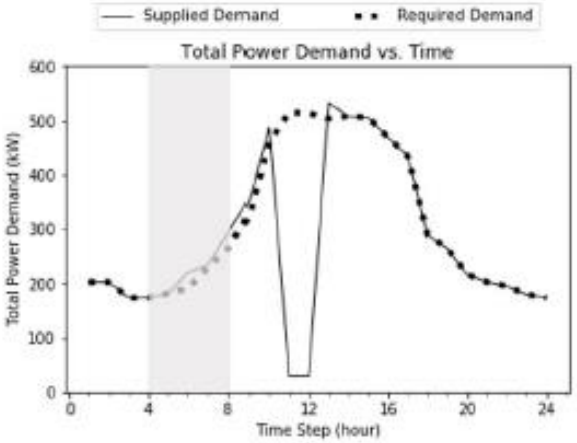

Pump Link Flowrate vs. Time
Time Step (hour)

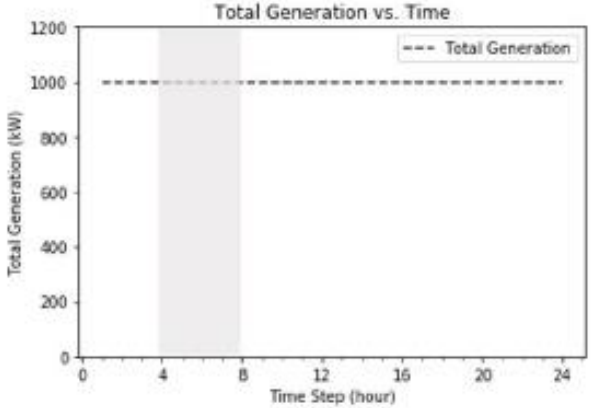

Tank Link Flowrate vs. Time
Time Step (hour)


Tank Level vs. Time
Time Step (hour)

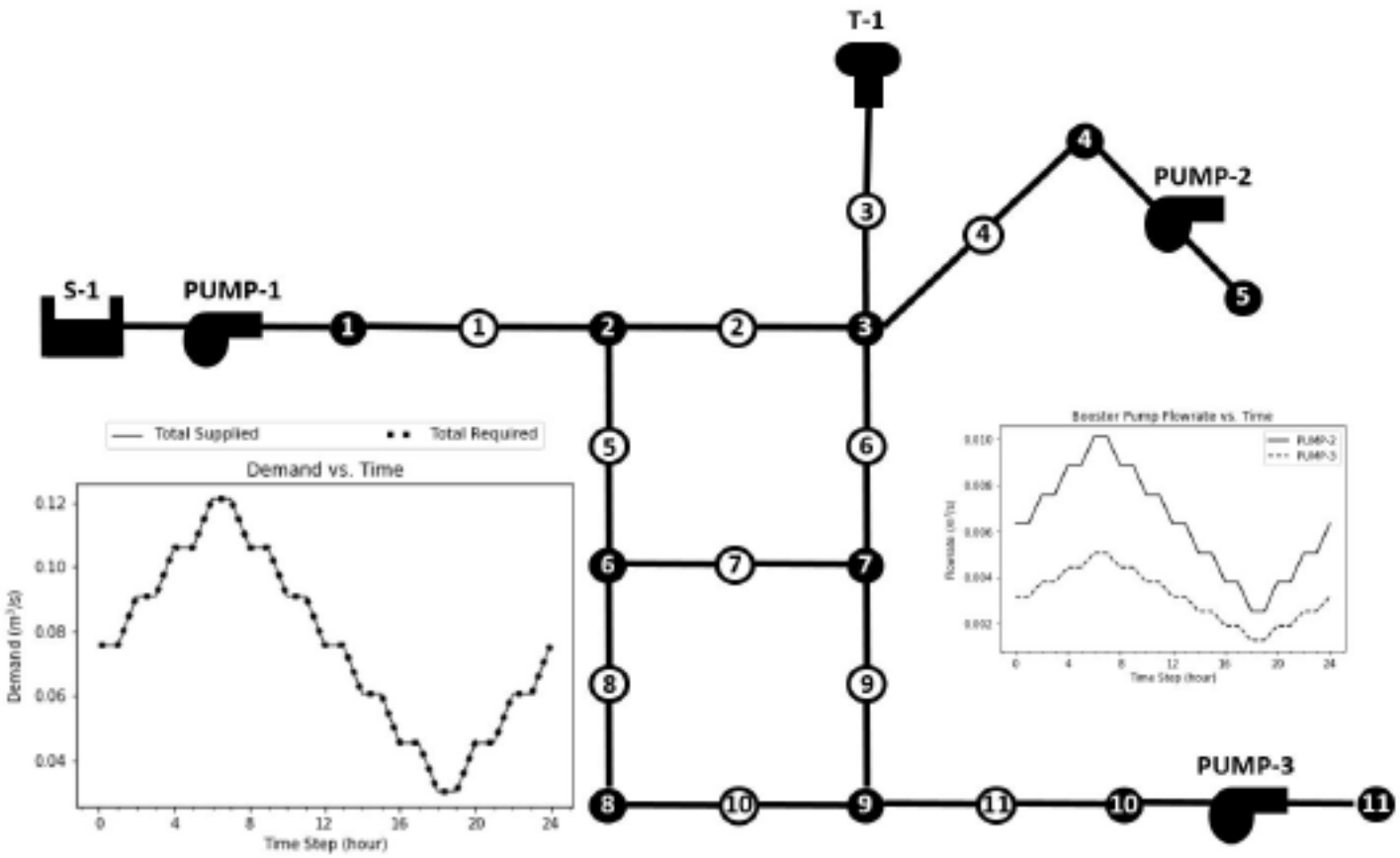

2
21
I. FIRE FLOW
4
3
31
1
1
2
II. OUTAGE
3
4
I. FIRE

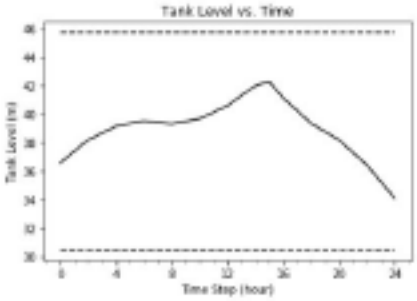

Node Pressure
Supplied Demand
Required Demand
Pressure and Demand vs. Time
Pressure (m)
Demand (m³/s)
Time Step (hour)
I

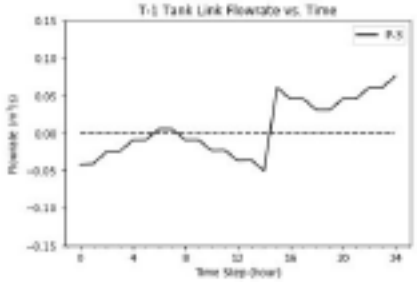

Supplied Demand
Required Demand
Total Power Demand vs. Time
Total Power Demand (kW)
Time Step (hour)

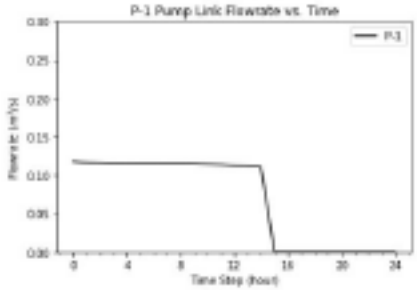

Total Generation vs. Time
Total Generation
Total Generation (kW)
Time Step (hour)

A more realistic (USVI) water distribution system

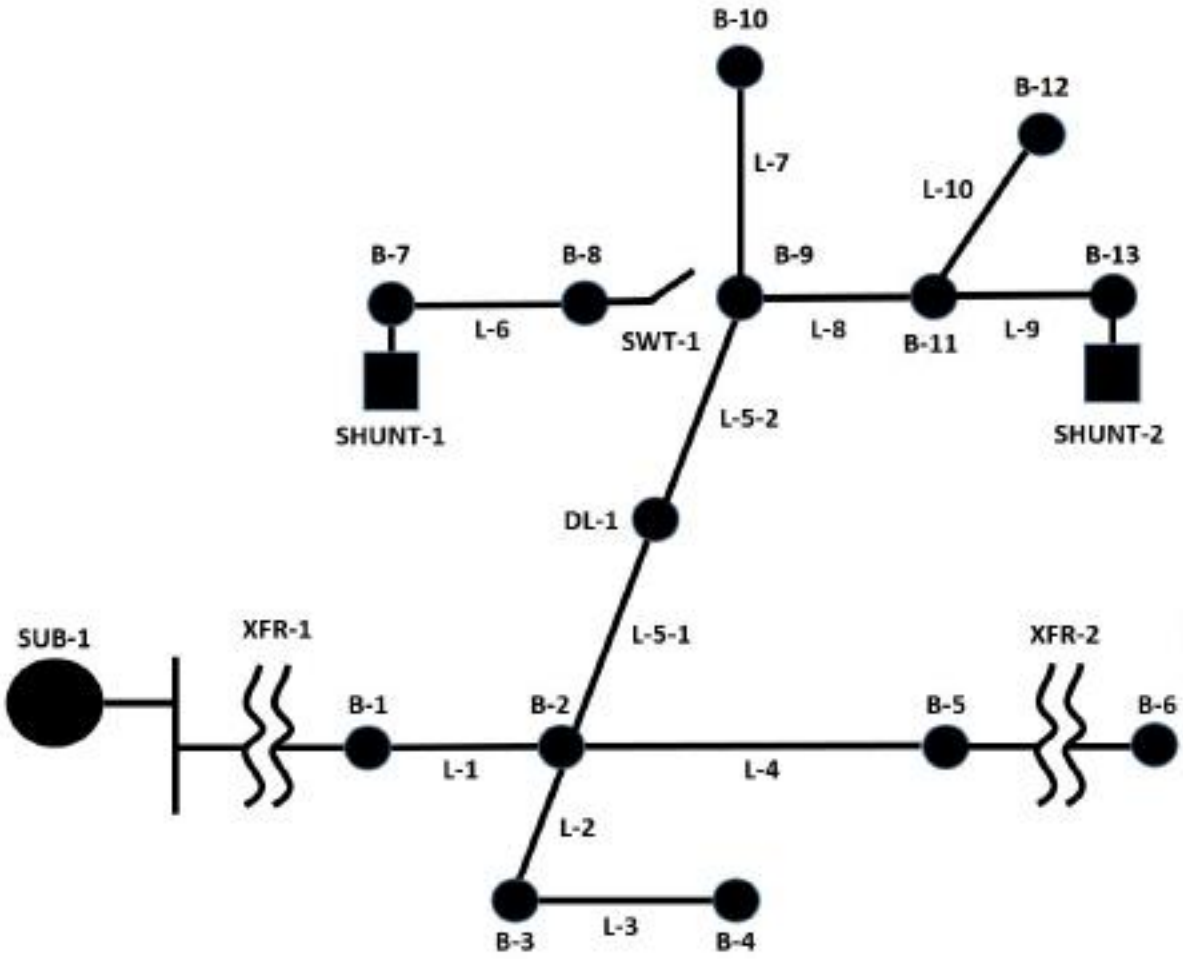


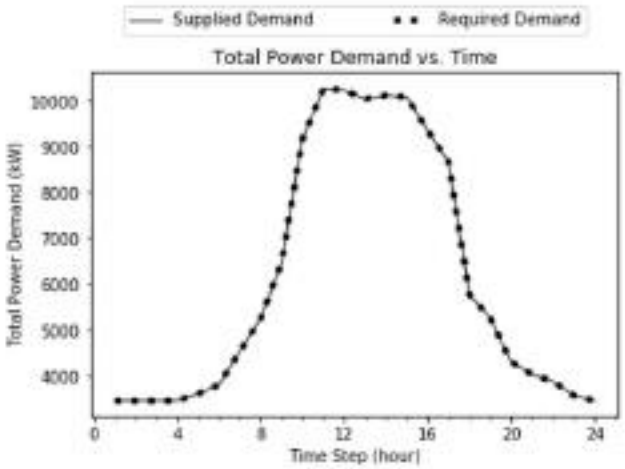


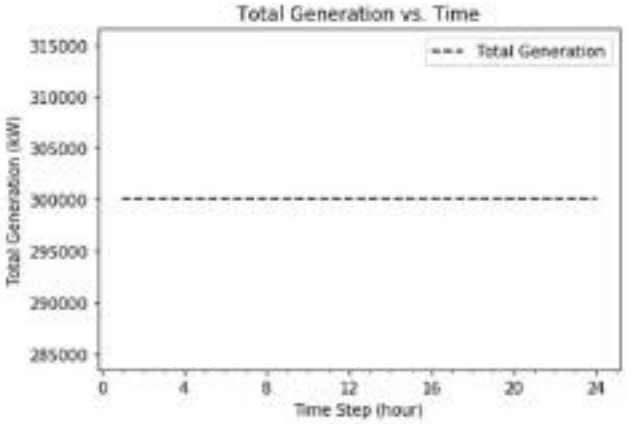


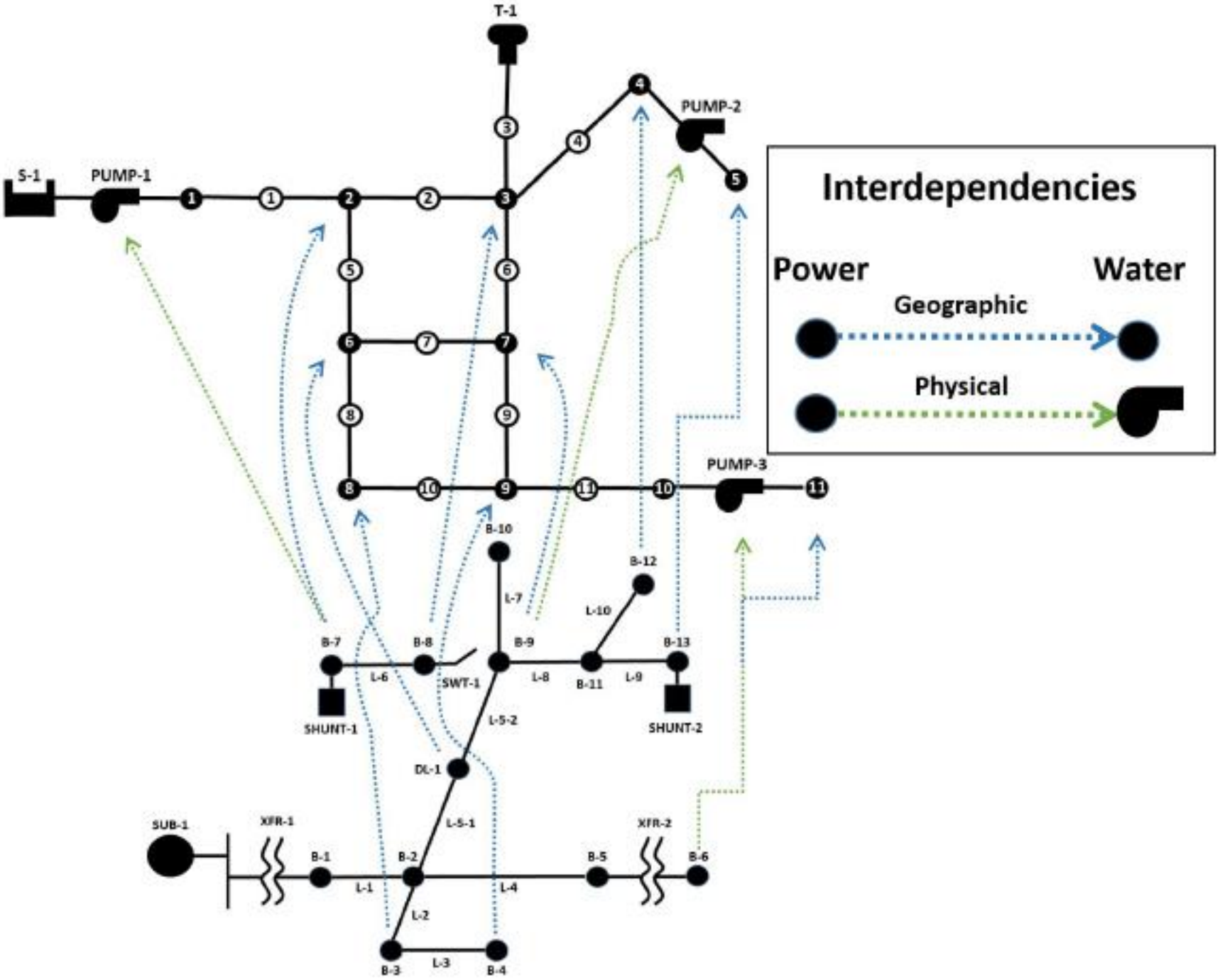


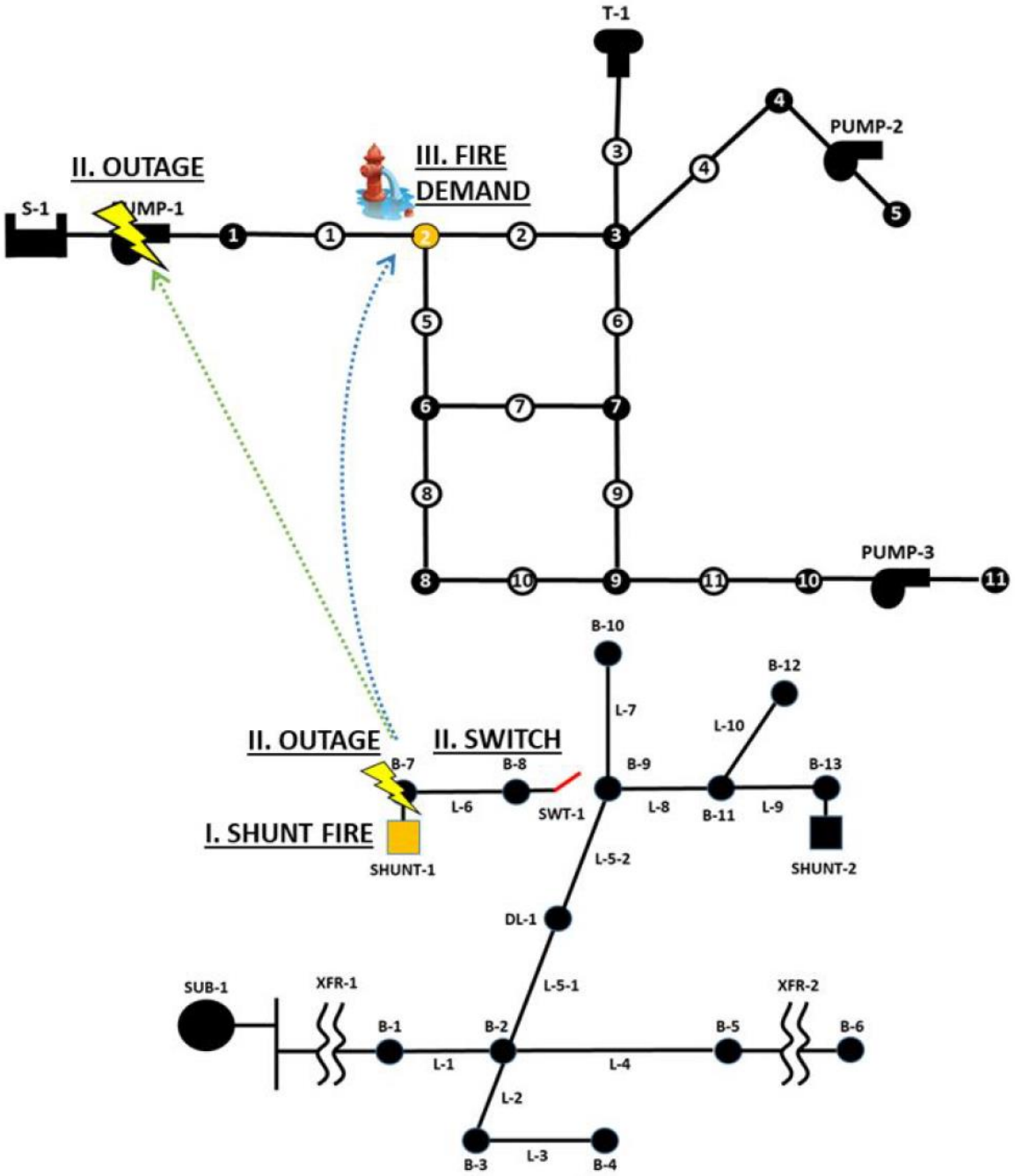
IEEE 13-bus electricity distribution network



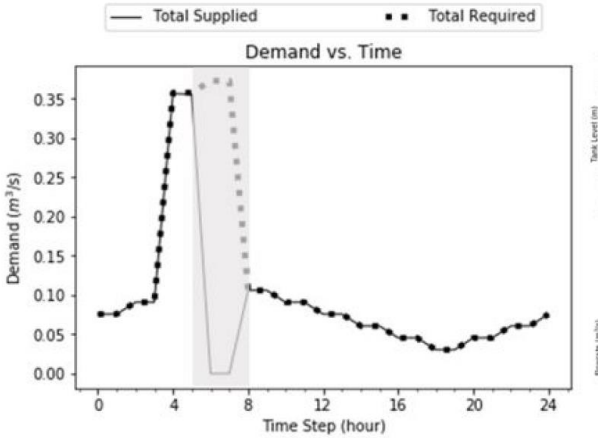


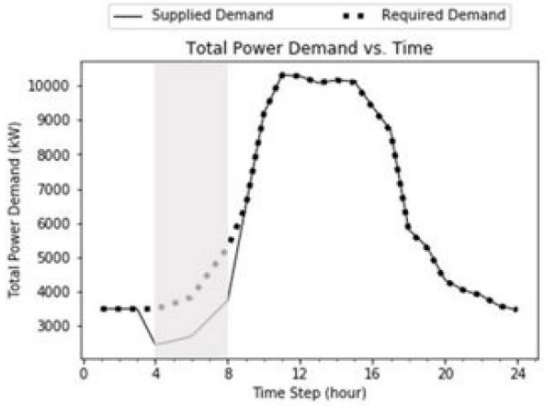



T-1
PUMP-2
S-1
PUMP-1
PUMP-3
Interdependencies
Power
Water
Geographic
Physical
B-10
B-12
L-7
L-10
B-7
B-8
B-9
B-13
L-6
SWT-1
L-8
B-11
L-9
SHUNT-1
SHUNT-2
L-5-2
DL-1
SUB-1
XFR-1
L-5-1
XFR-2
B-1
B-2
B-5
B-6
L-1
L-4
L-2
B-3
L-3
B-4


T-1
PUMP-2
PUMP-3
II. OUTAGE
III. FIRE
DEMAND
S-1
II. OUTAGE
II. SWITCH
I. SHUNT FIRE
SHUNT-1
SHUNT-2
SWT-1
B-10
B-12
B-13
L-7
L-10
L-8
L-9
L-6
B-7
B-8
B-9
B-11
L-5-2
DL-1
L-5-1
SUB-1
XFR-1
XFR-2
B-1
B-2
B-5
B-6
L-1
L-4
L-2
B-3
L-3
B-4

(a)


Total Supplied
Total Required
Demand vs. Time
Demand (m^3/s)
Time Step (hour)


Supplied Demand
Required Demand
Total Power Demand vs. Time
Total Power Demand (kW)
Time Step (hour)

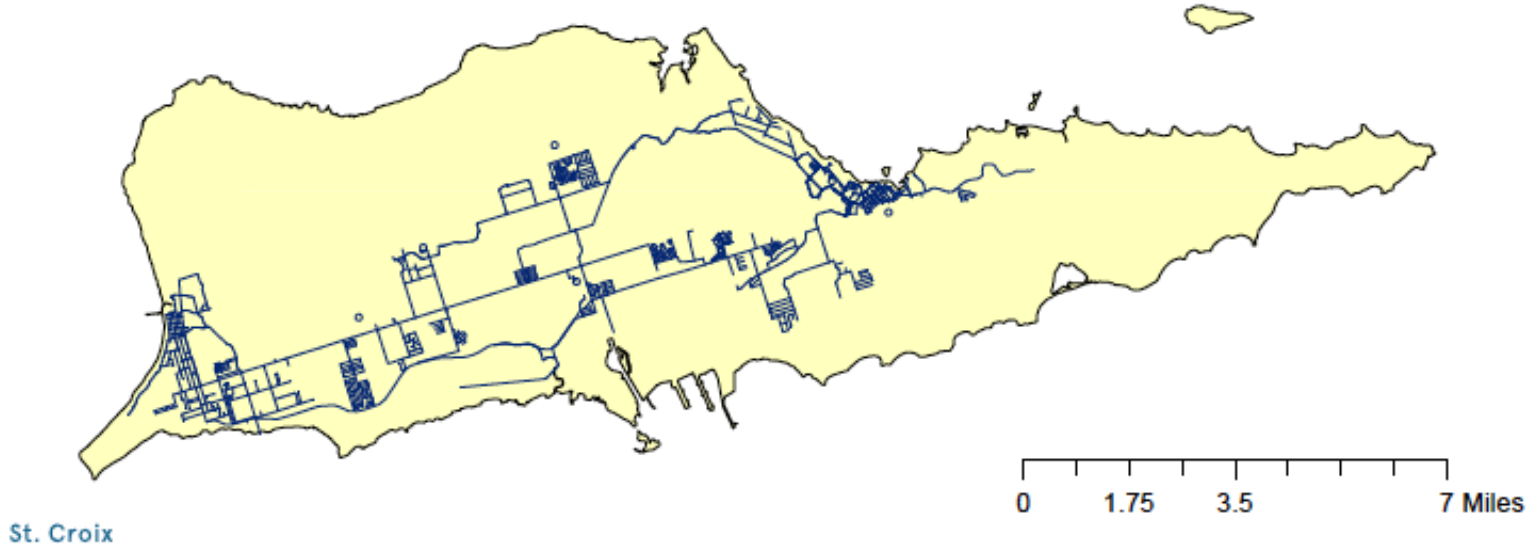
Summary and Conclusions

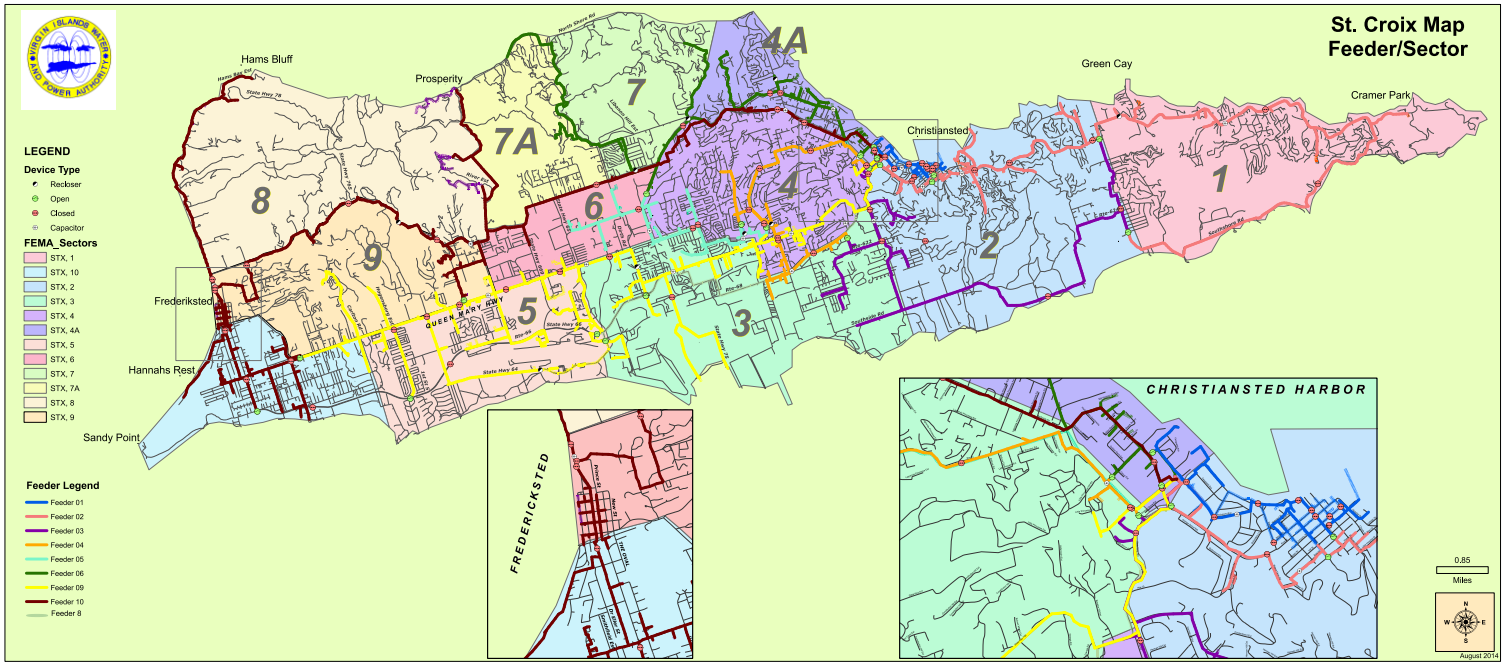
- An operator model is needed to guide resilience initiatives
  - Too many initiatives to grasp for a single org
  - Need to understand the USVI **before** the hurricanes

- **USVI Infrastructure Operations & Chronic Problems**
  - Issues in system design, operation, and economics
  - Recovery / redesign requires knowledge about interdependent vulnerabilities and plans

- Need for interdependent models that match context
  - Existing water-power models designed with inappropriate physics / needs
  - **Lack of standard models for testing and validation**
  - Initial results show that simple interdependencies = systemic changes in operations

Ongoing work: Scaling up to St. Croix





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
- Telecommunications

Effort 2 - Support for development of a new Hazard Mitigation and Resilience Plan

- in partnership with UVI / VITEMA

Effort 3 - Capacity building & workforce development program

- in partnership with UVI

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- NPS Center for Infrastructure Defense

  Director: Dr. David Alderson

  http://www.nps.edu/cid

- Backup, unused slides

References and Acknowledgments

- Alderson, D.L., Brown, G., Carlyle, W.M., and Wood, R.K., 2017, **"Assessing and Improving the Operational Resilience of a Large Highway Infrastructure System to Worst-Case Losses,"** *Transportation Science*, doi.org/10.1287/trsc.2017.0749.
- Alderson, D.L., Brown, G., and Carlyle, W.M., 2015, **"Operational Models of Infrastructure Resilience,"** *Risk Analysis* 35(4): 562-586 (received Award for Best Paper of 2015 in Risk Analysis).
- Alderson, D.L., G.G. Brown, W.M. Carlyle. 2014. **"Assessing and Improving Operational Resilience of Critical Infrastructures and Other Systems."** A. Newman, J. Leung, eds., *Tutorials in Operations Research: Bridging Data and Decision*. Institute for Operations Research and Management Science, Hanover, MD, 180-215.
- Alderson, D.L., G.G. Brown, W.M. Carlyle, L.A. Cox. 2013. **"Sometimes there is no 'most vital' arc: assessing and improving the operational resilience of systems."** *Military Operations Research* 18(1) 21-37.
- Brown, G., Carlyle, M., Salmerón, J. and Wood, K., 2006, **"Defending Critical Infrastructure,"** *Interfaces*, 36, pp. 530-544.

This research was supported by the Office of Naval Research, the Air Force Office of Scientific Research, and the Defense Threat Reduction Agency.

What is Critical Infrastructure?

- ***Critical Infrastructure (CI)***: "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" ***--Section 1016(e) of the USA PATRIOT Act of 2001***











Critical Infrastructure Systems: NPS has a unique perspective and capability

- We have been studying critical infrastructure for decades.
- We look at our own domestic infrastructure through the eyes of intelligent adversaries.
- We have conducted over 150 “red team analyses” to plan attacks on our own infrastructure (and determine how to mount effective hardening and defensive efforts)

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Goals For This Session

- **10 key ideas** for how to assess and improve operational resilience of critical infrastructures
- Ongoing work in applying these ideas to the USVI