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

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Research Assistant Professor | Operations Research
Deputy Director | Center for Infrastructure Defense
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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

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

Daniel Eisenberg
Research Assistant Professor, OR
Deputy Director, NPS CID

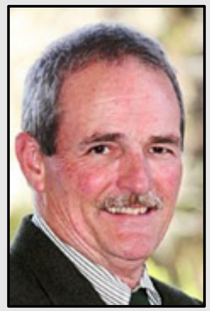
Ph.D., Arizona State University, 2018

W. Matthew Carlyle
Professor & Chair, OR

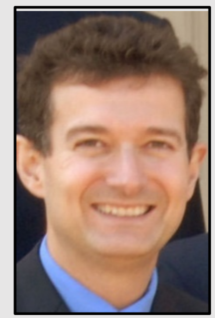
Ph.D., Stanford University, 1997

Robert Dell
Professor, OR

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



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



Javier Salmerón
Associate Professor, OR

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

Cross-Campus Collaborators

Jefferson Huang
Assistant Professor, OR

Ph.D., Cornell, 2017

Alan Howard
Deputy Director, NPS Energy Academic Group

MBA/MIM in International Management, 2000

Justin Rohrer
Assistant Professor, CS

Ph.D., University of Kansas, 2011

Research is Part of a Broader Team Effort

FEMA

U.S. DEPARTMENT OF ENERGY

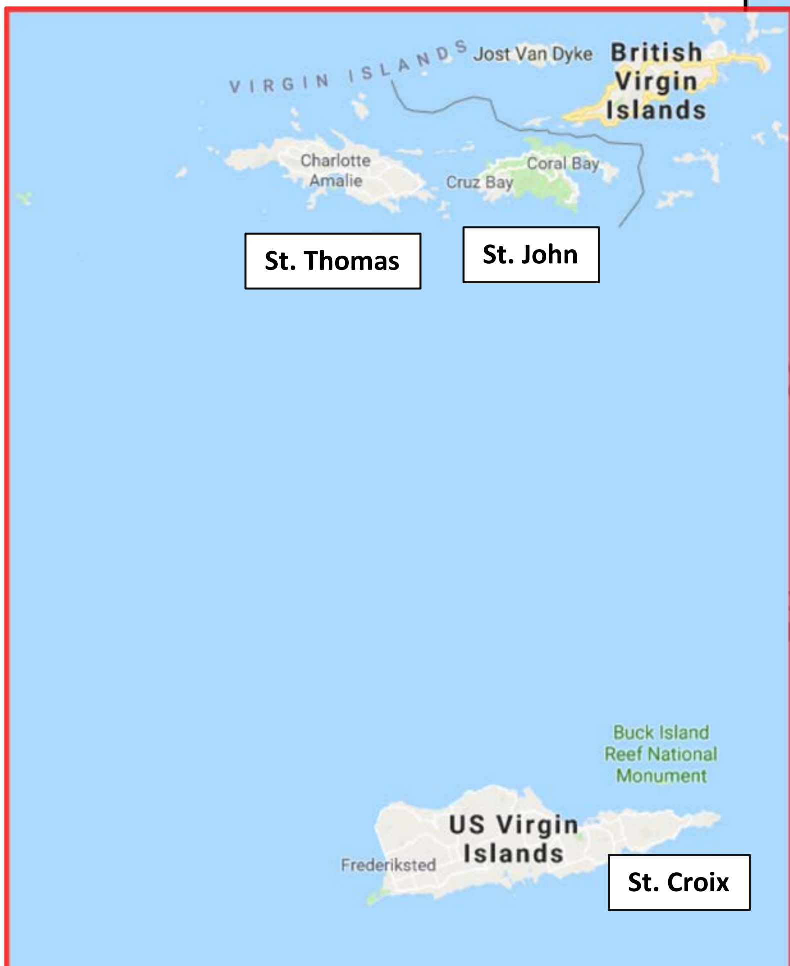
NAVAL POSTGRADUATE SCHOOL

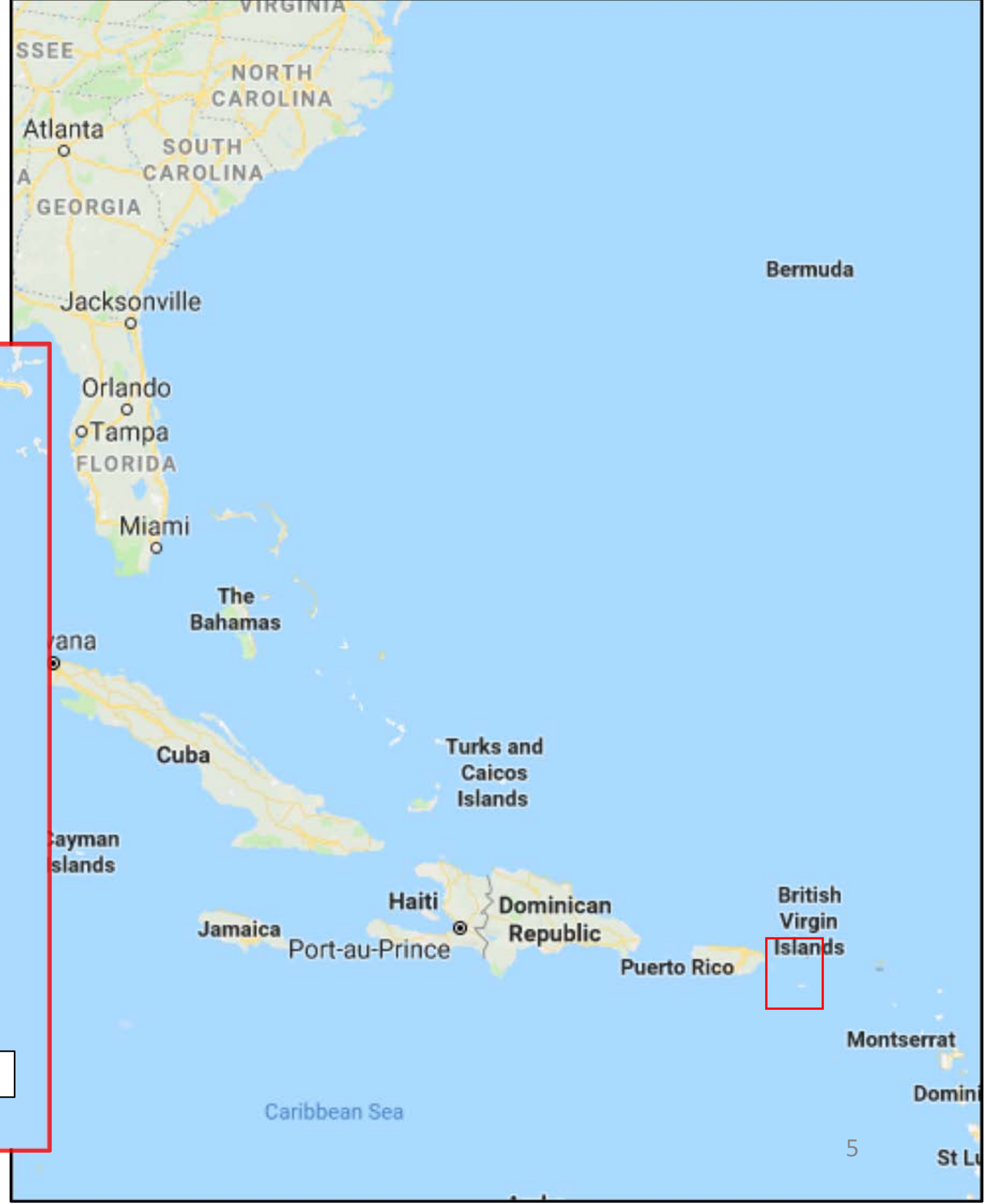
University of the Virgin Islands

Storm Characteristics

FL → PR → STT → STJ

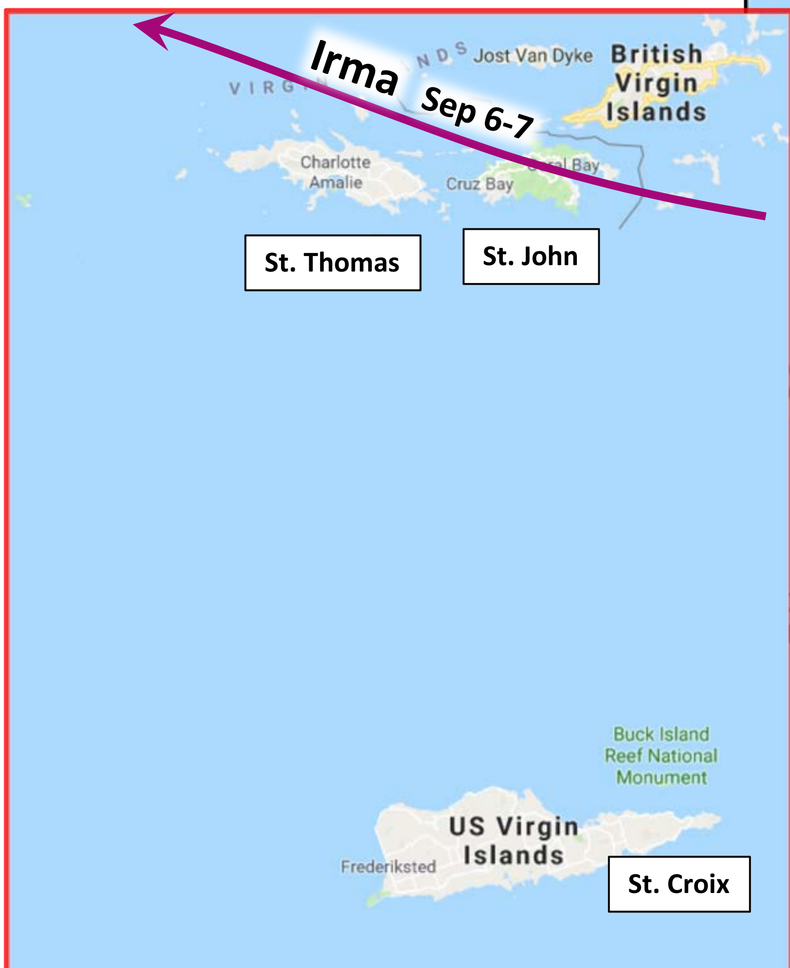
STT → STX → DI



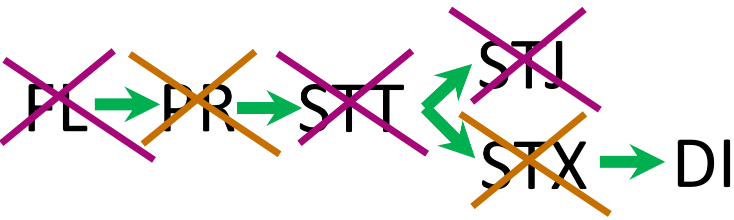


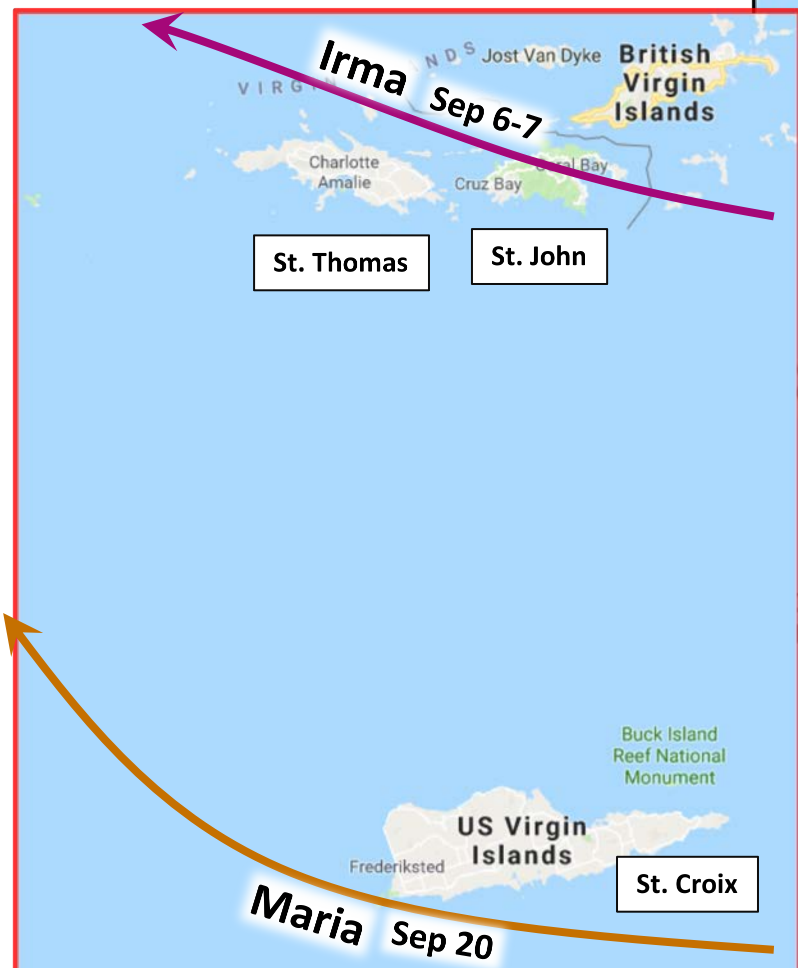
Storm Characteristics

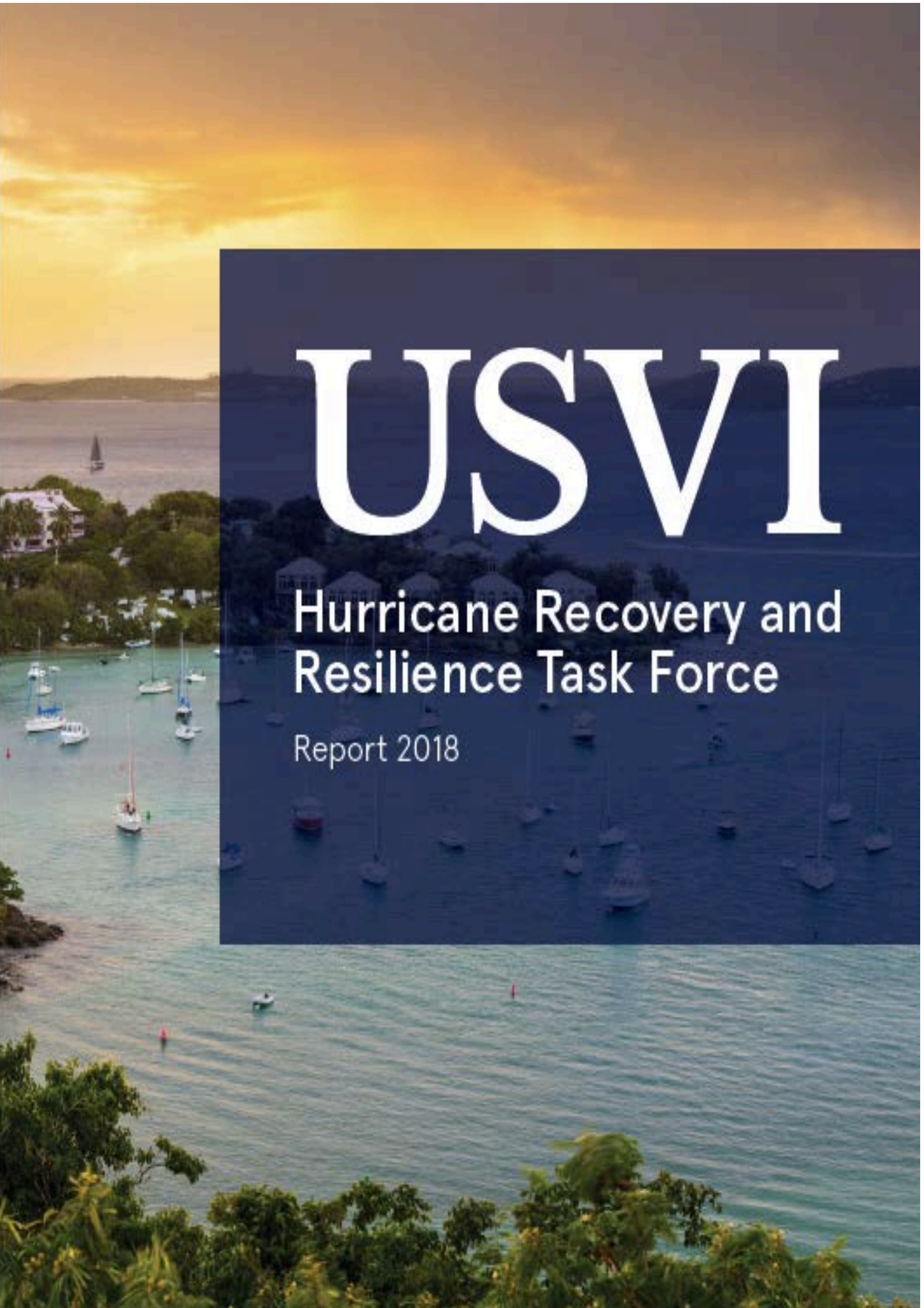
~~FL~~ → PR → ~~STT~~ → ~~STJ~~ / STX → DI



Storm Characteristics







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

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

Infrastructure Mission in the DoD

DOD Directive 3020.40: Mission Assurance (2016)

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:

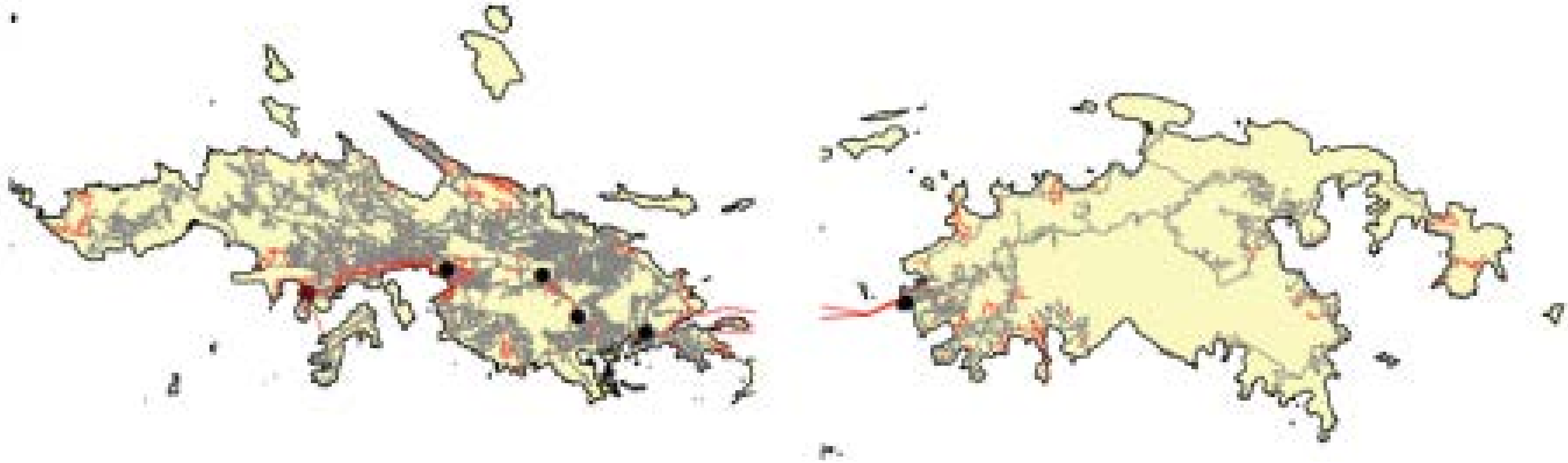
- NAVFAC: 7 Days Energy (NAVFAC P-602, 2017)
- ARMY: 2 Weeks Energy + Water (Army Directive 2017-07)
- USAF: 7 Days Energy (USAF Directive 90-17)
- USMC: 2 Weeks Energy + Water (Logistics, Comms, & Food)

Infrastructure Service Recovery Timeline – Electricity

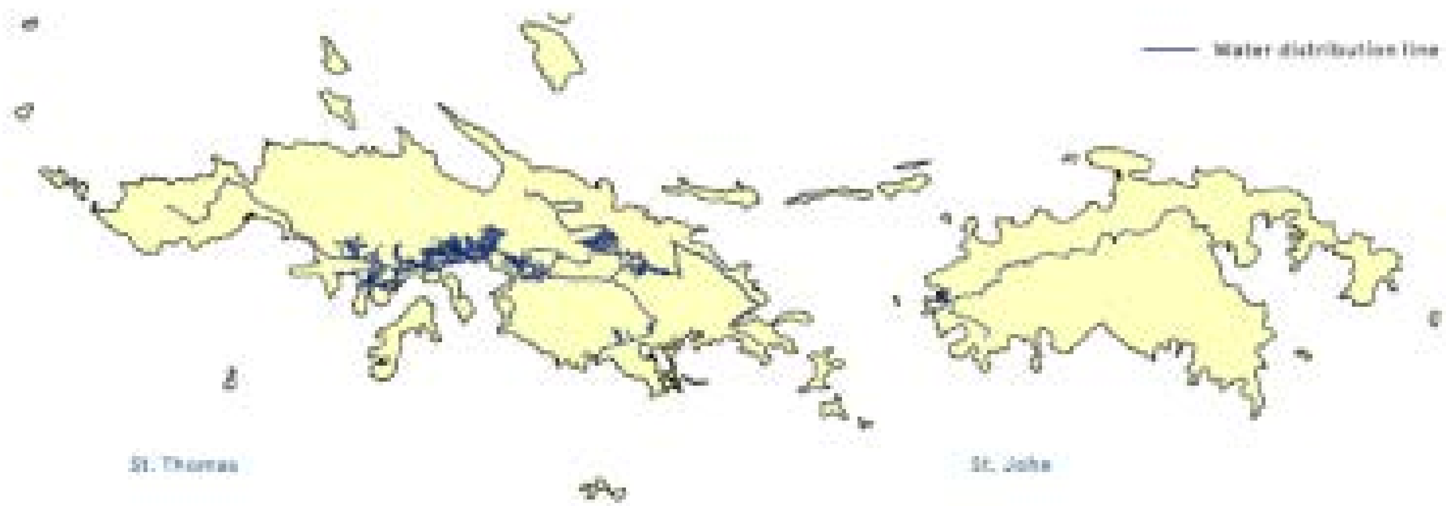
Hurricanes **1 Month** **2 Months** **3 Months**

Resilience Depends on System Design – STT/STJ

Electricity Distribution System



Water Distribution System



Resilience Depends on System Design – STT/STJ

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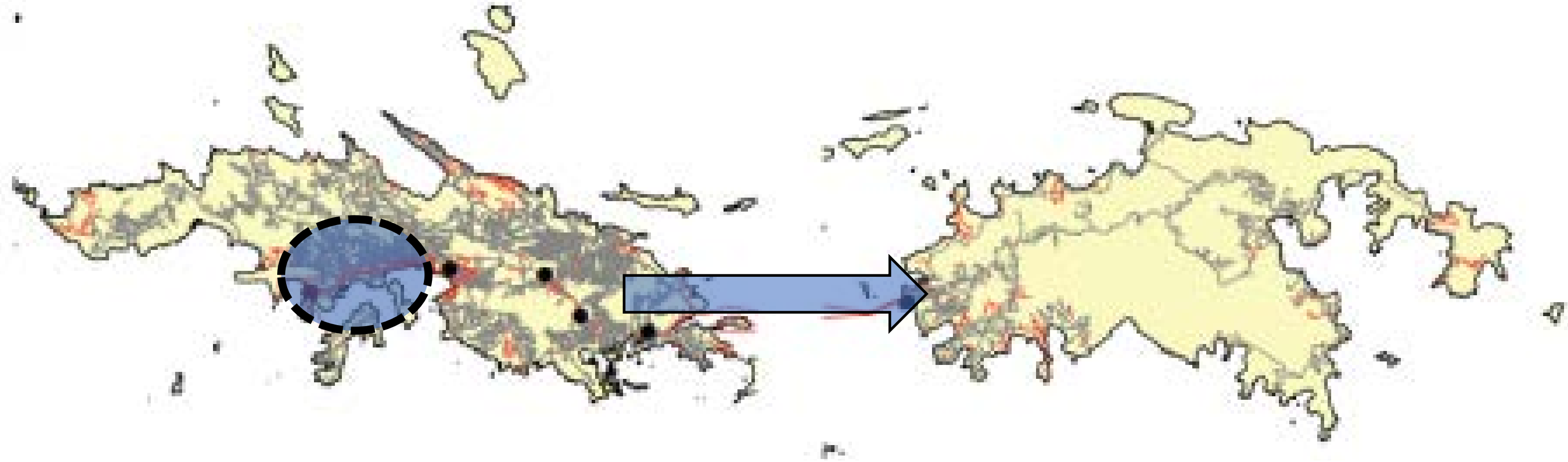
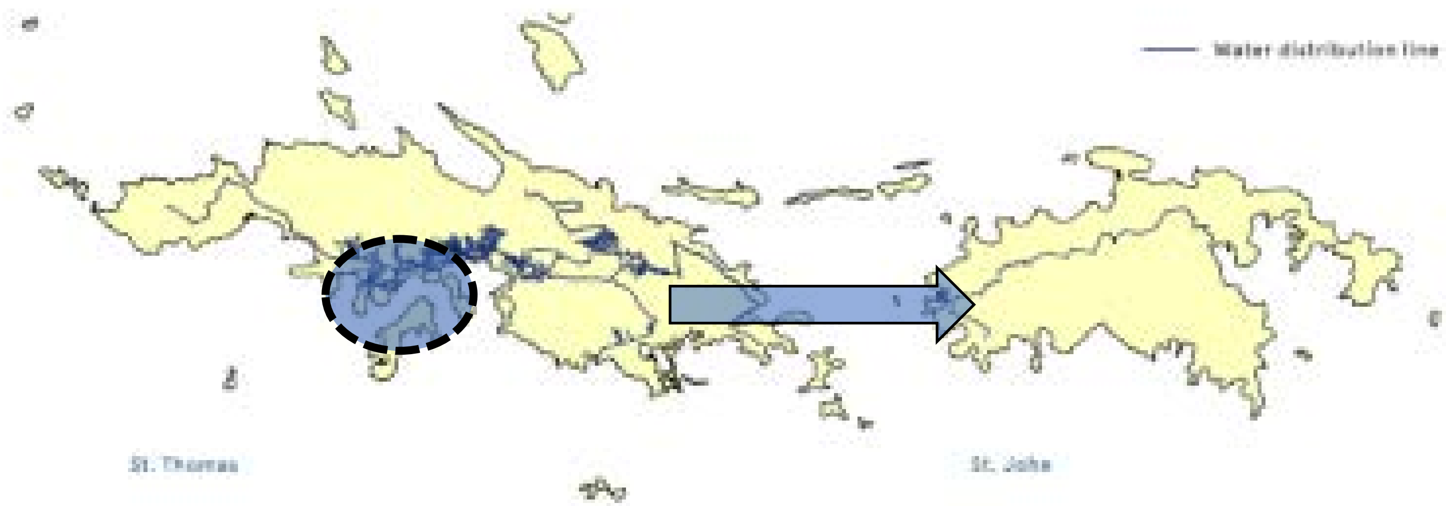
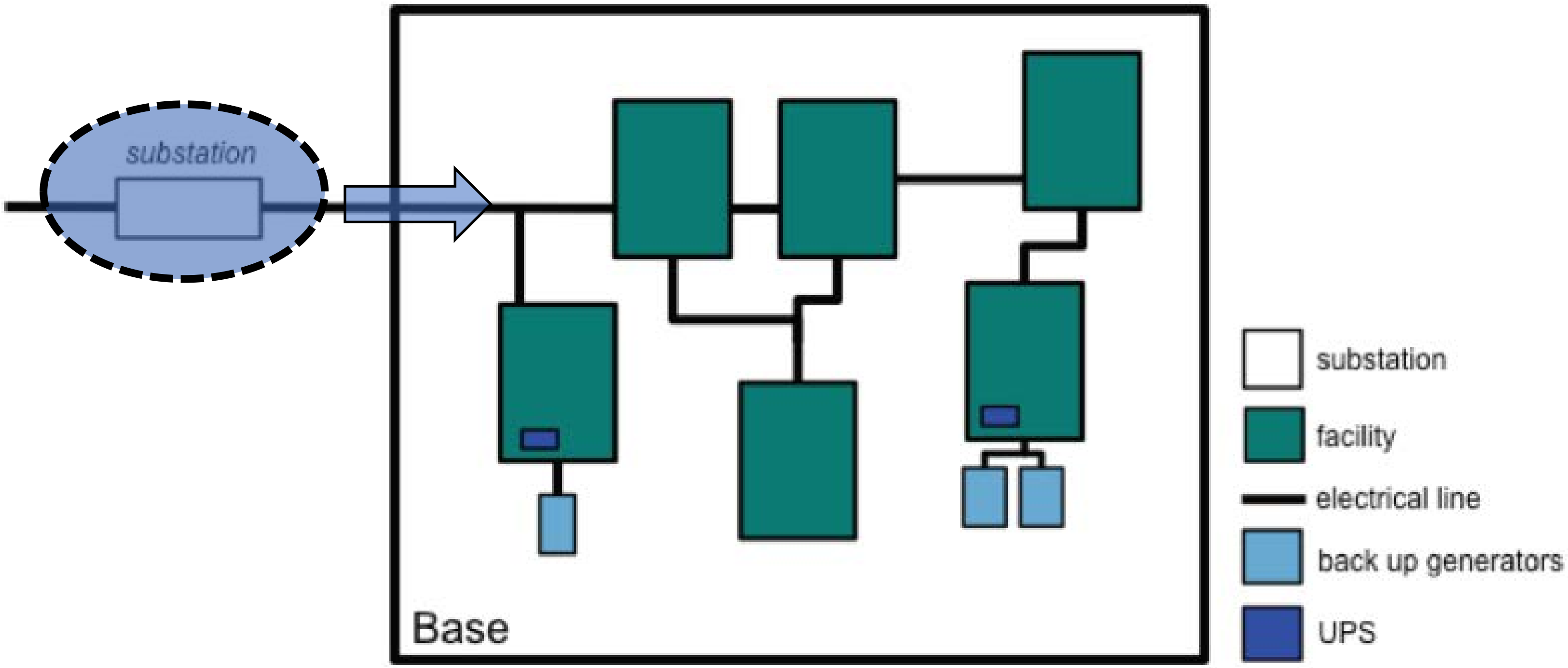


Water Distribution System



Relating Islands to Military Installations

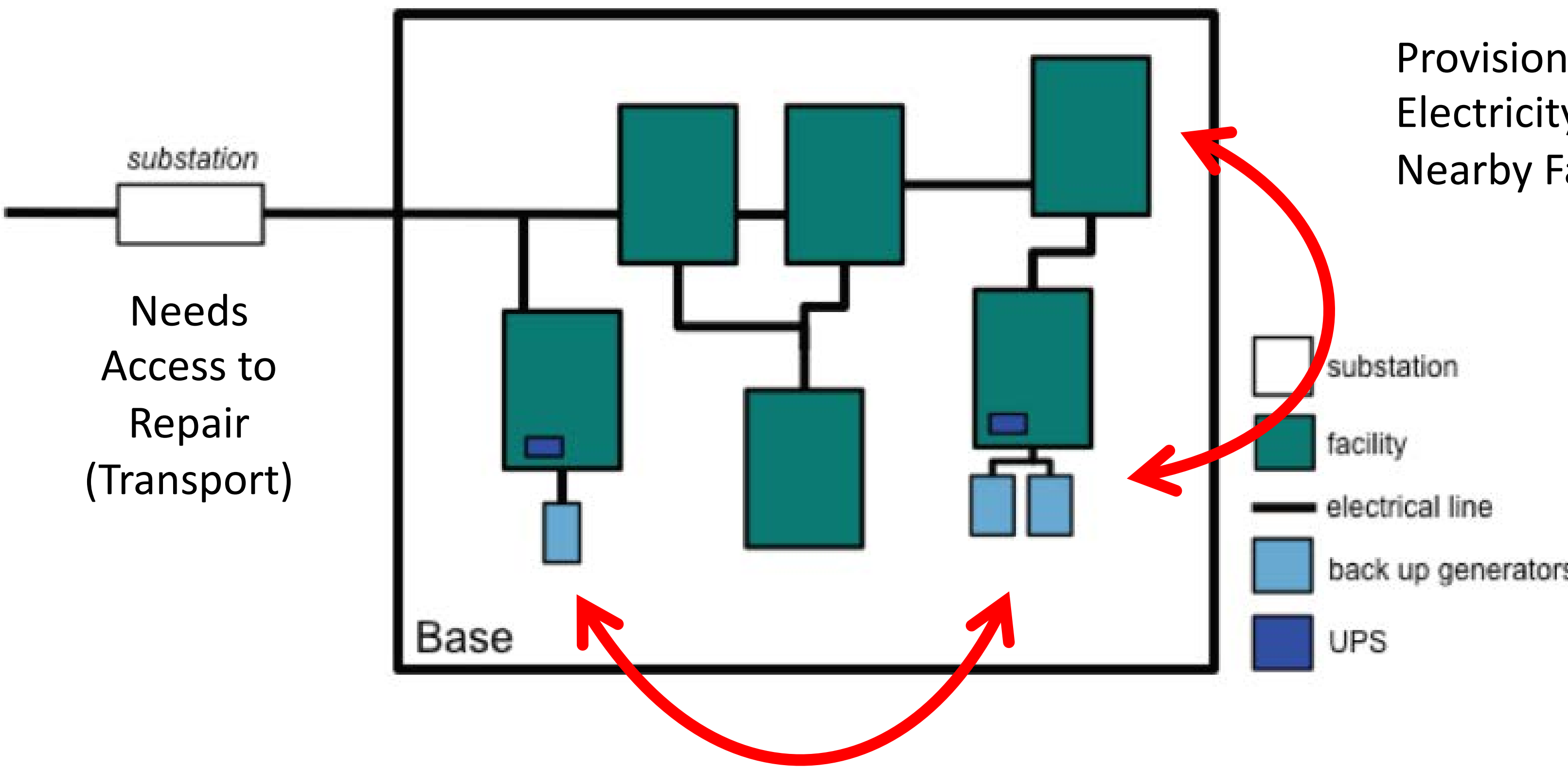
Figure 3.1. Conceptual Diagram of CONUS Base Electric Power Physical Infrastructure



Narayanan, Anu, Debra Knopman, James D. Powers, Bryan Boling, Benjamin M. Miller, Patrick Mills, Kristin Van Abel, Katherine Anania, Blake Cignarella, and Connor P. Jackson. *Air Force Installation Energy Assurance*. RAND Corporation, 2017.

Relating Islands to Military Installations

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



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:

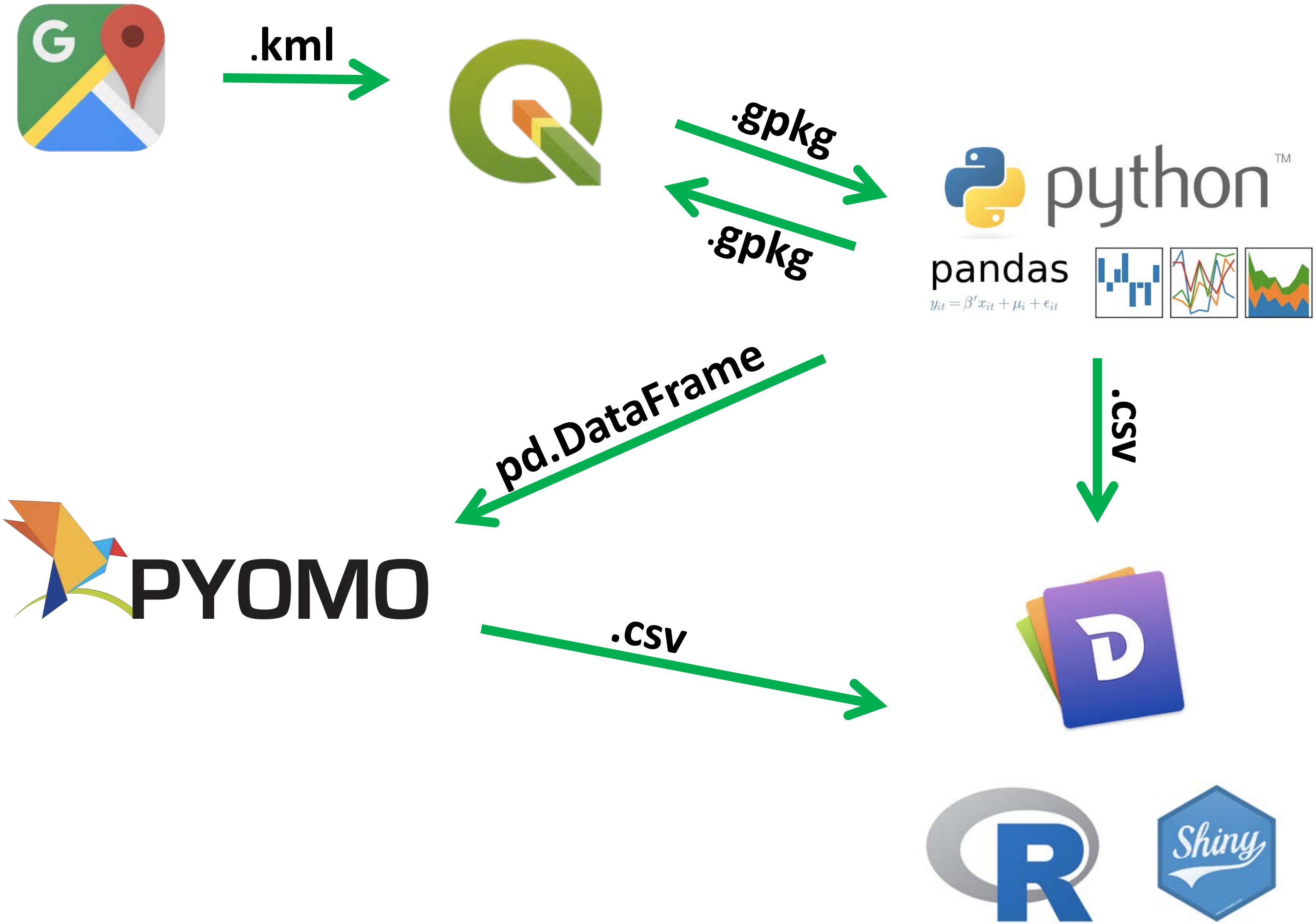
- Community access to disaster relief during and after hurricanes
- Drainage infrastructure condition, roadway flooding, and traffic impacts

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



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PYOMO
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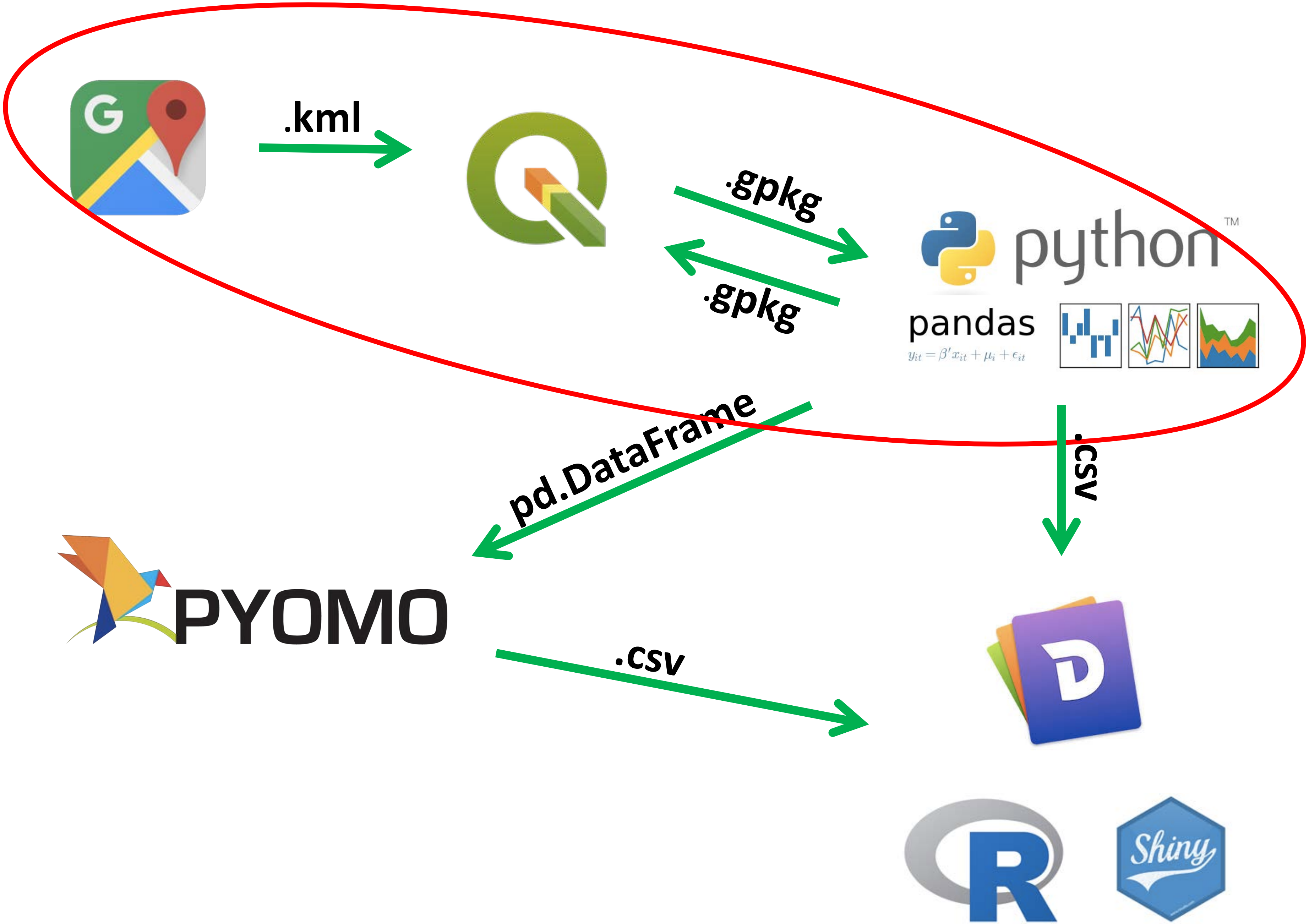
Shiny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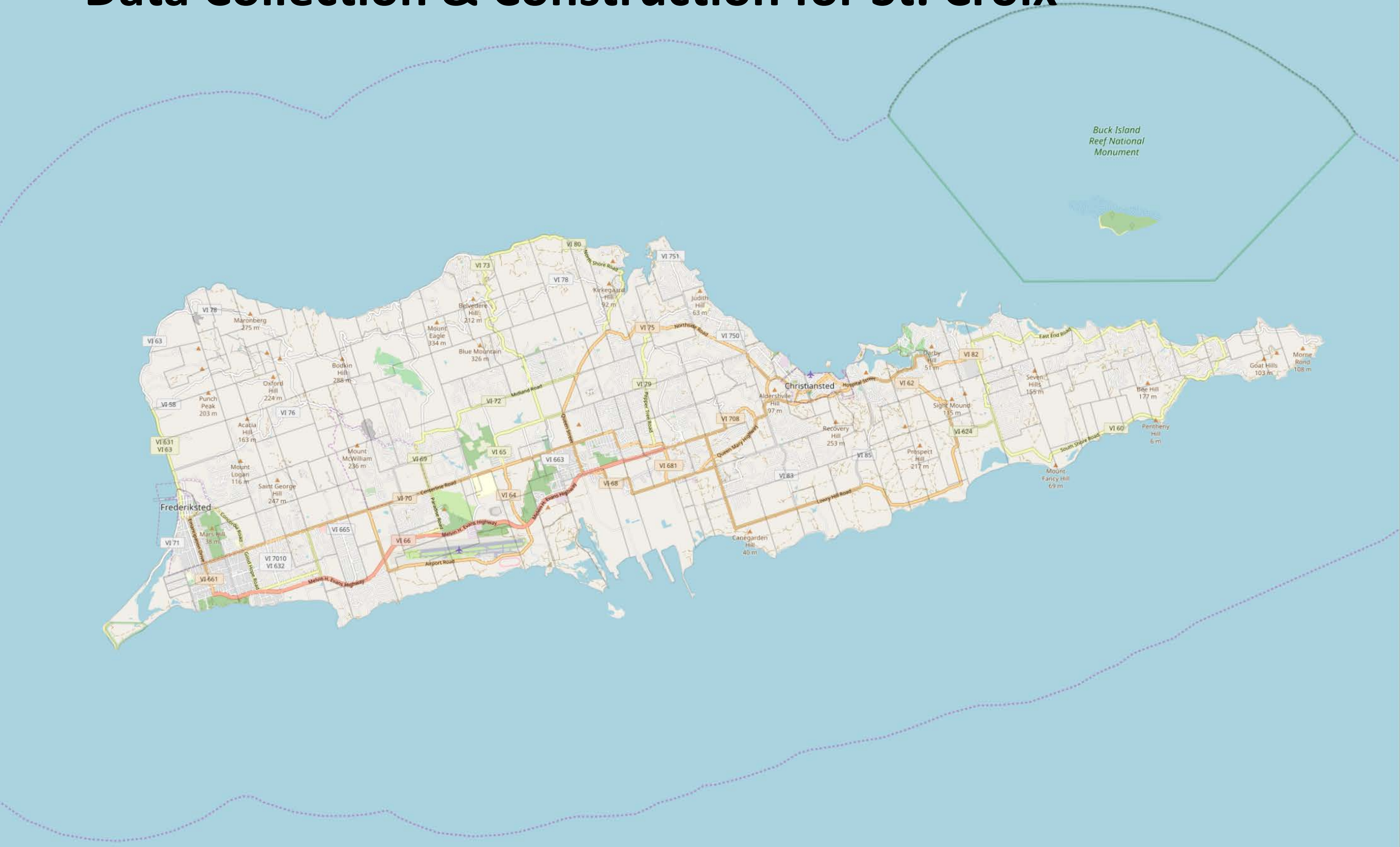
Data Collection & Construction for St. Croix

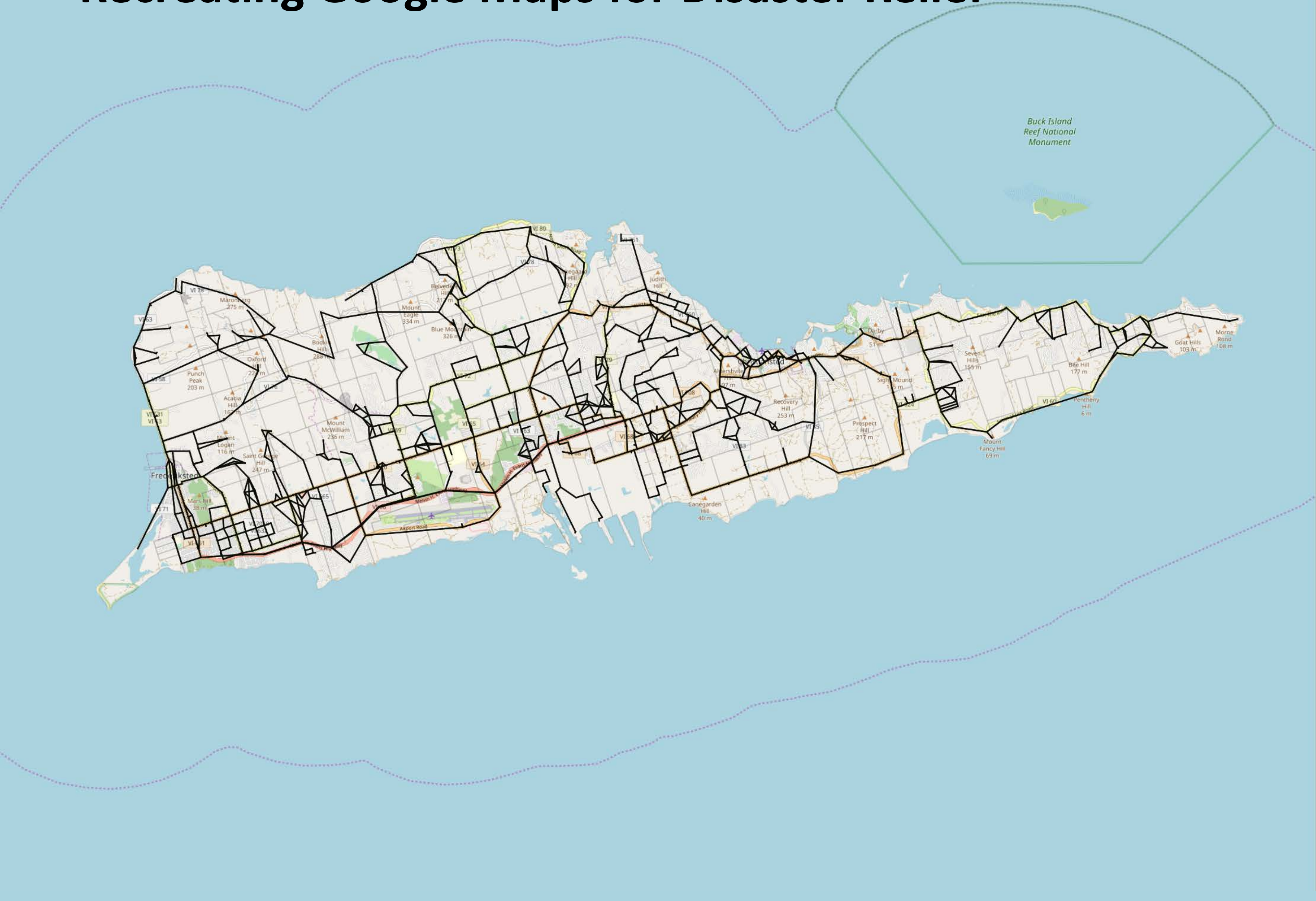
26-30 Mar	1st NPS site visit to STX, STT
11-15 Jun	2nd NPS site visit to STX, STT
14-15 Jun	UVI/VITEMA Hazard Mitigation Workshop
22-26 Oct	3rd NPS site visit to STX, STJ, STT
24-25 Oct	Sandia Microgrid Workshops
24-29 Mar	4th Site Visit to STX, STJ, STT
09-13 Sept	Planned: 5th Site Visit & 2nd HMP Workshop

- 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.
- Alderson DL, Bunn BB, Eisenberg DA, Howard AH, Nussbaum DE, Templeton JC, 2018, **"Interdependent Infrastructure Resilience in the U.S. Virgin Islands: Preliminary Assessment,"** NPS Technical Report, Naval Postgraduate School, Monterey, CA.

Data Collection & Construction for St. Croix



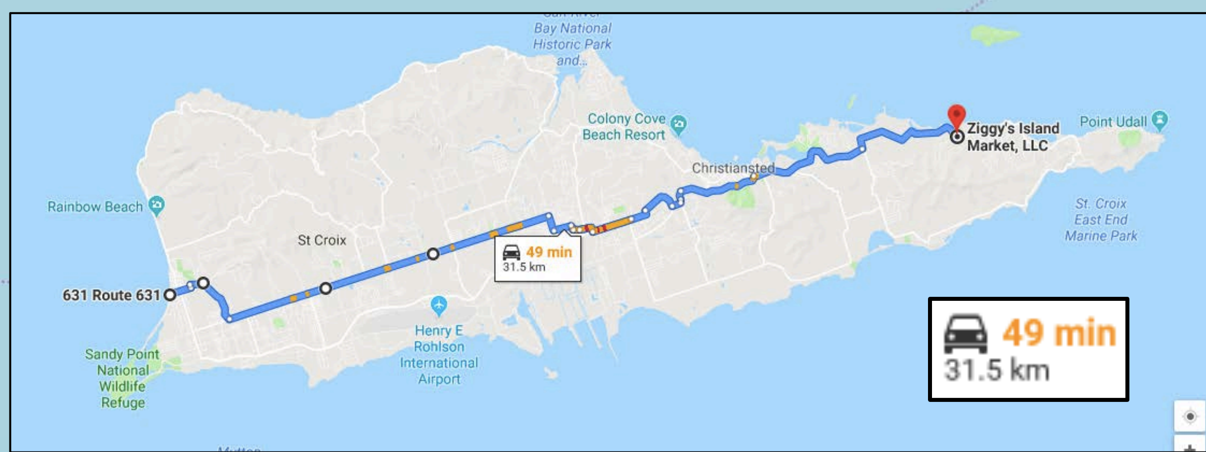
Recreating Google Maps for Disaster Relief



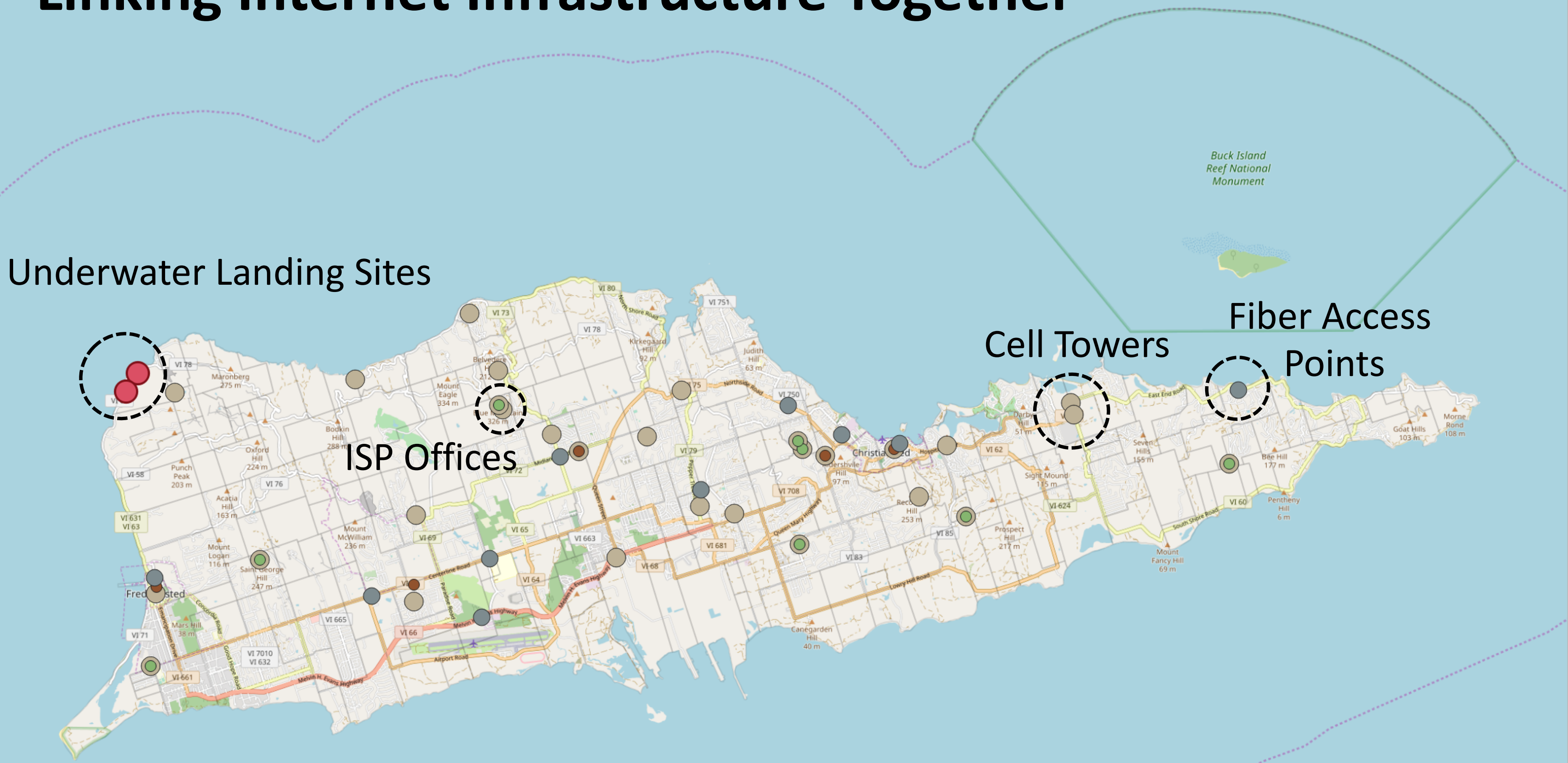
Recreating Google Maps for Disaster Relief

```
Running program:  ShortestPath.py
AllPoints file:  ../Data/Working/STX/ModelPostTrip/AllPointsSTX.json
AdjList file: : ../Data/Working/STX/ModelPostTrip/AdjDict.json
Origin Node:  O001
Destination Node:  G025

The distance from O001 to G025 is 31.164 km.
```



Linking Internet Infrastructure Together

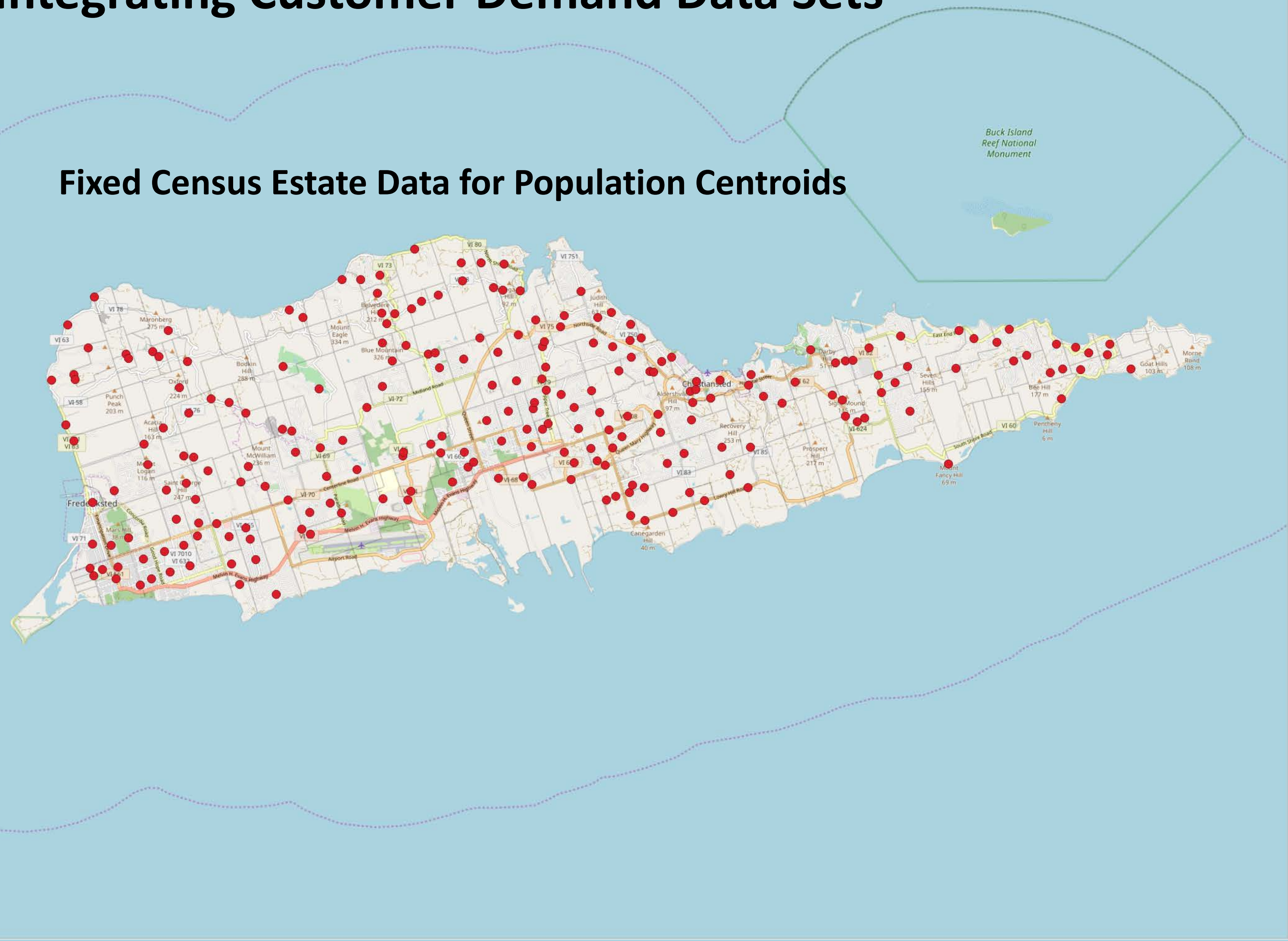


Linking the Infrastructure Together

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

Integrating Customer Demand Data Sets

Fixed Census Estate Data for Population Centroids



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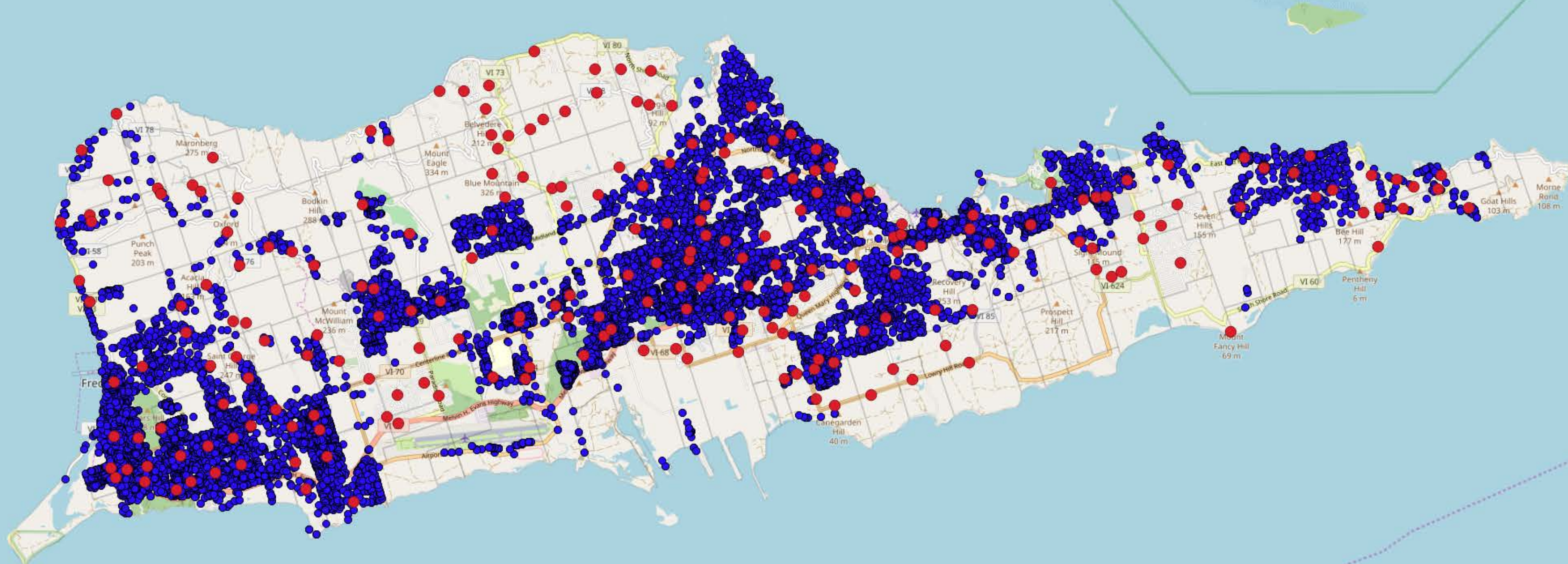
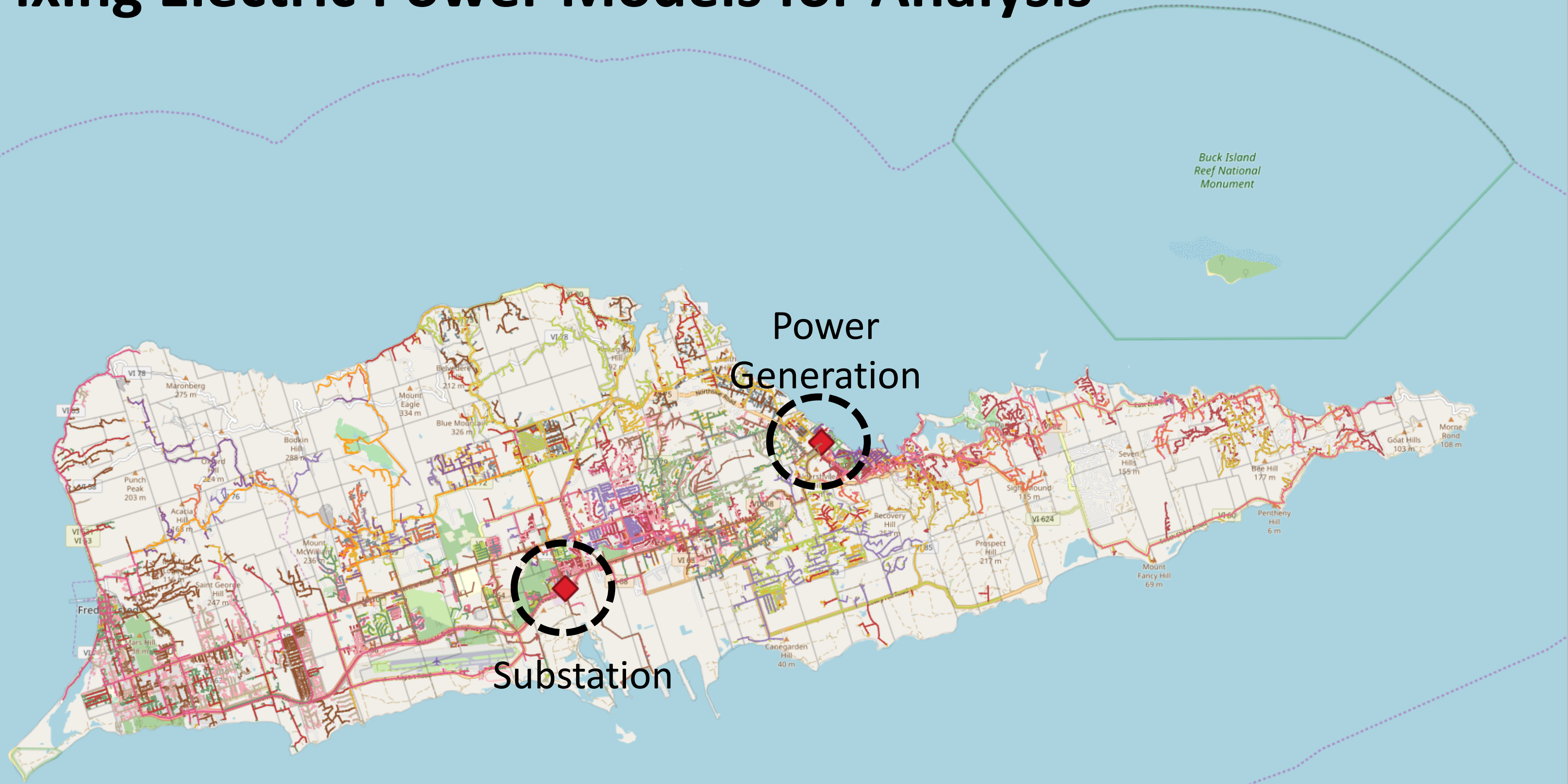


Relating electric power demand locations to census data…
goal to estimate related electric power, transportation, and water demands

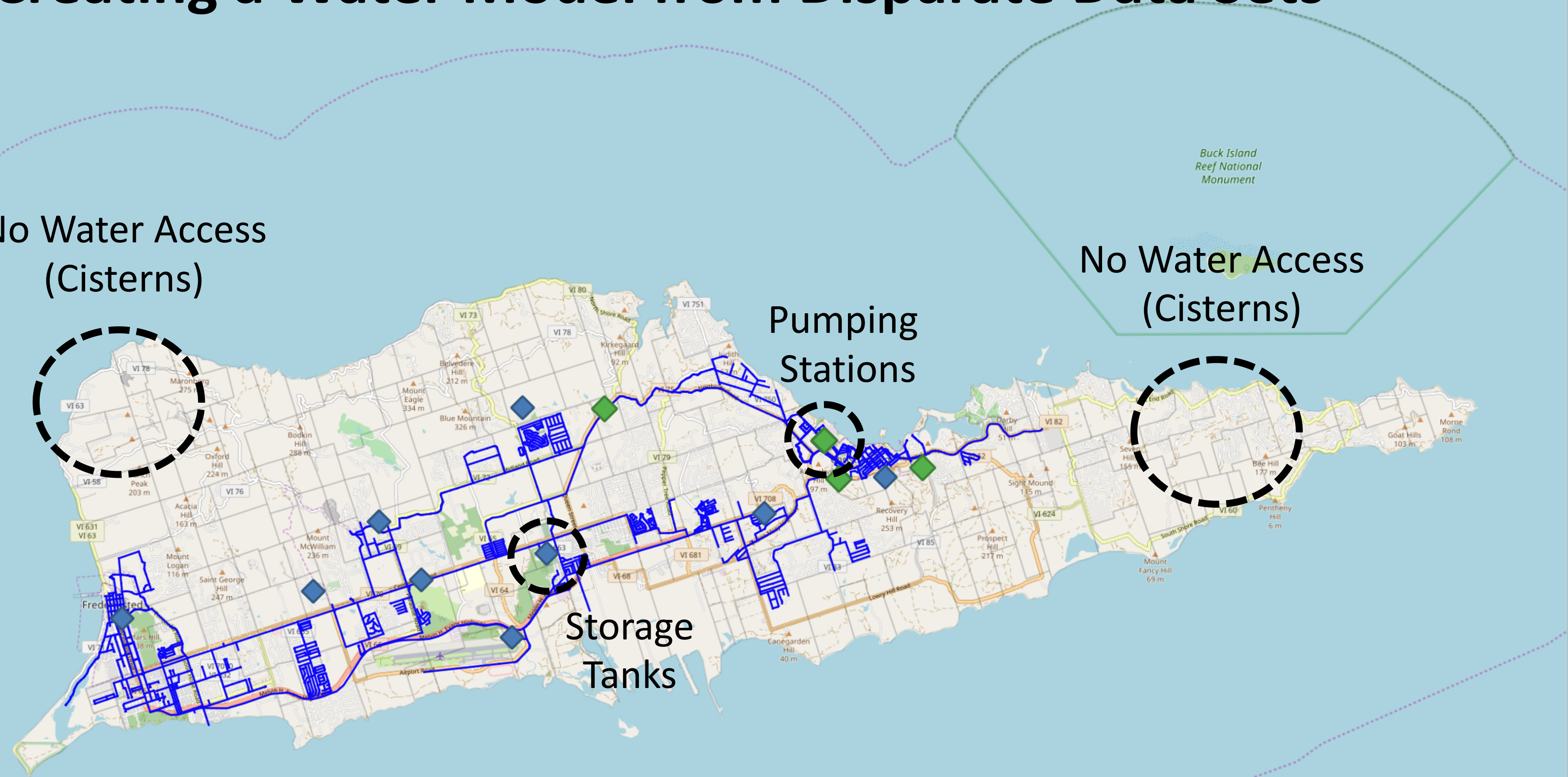
Fixing Electric Power Models for Analysis



Issues with Electricity Utility Data

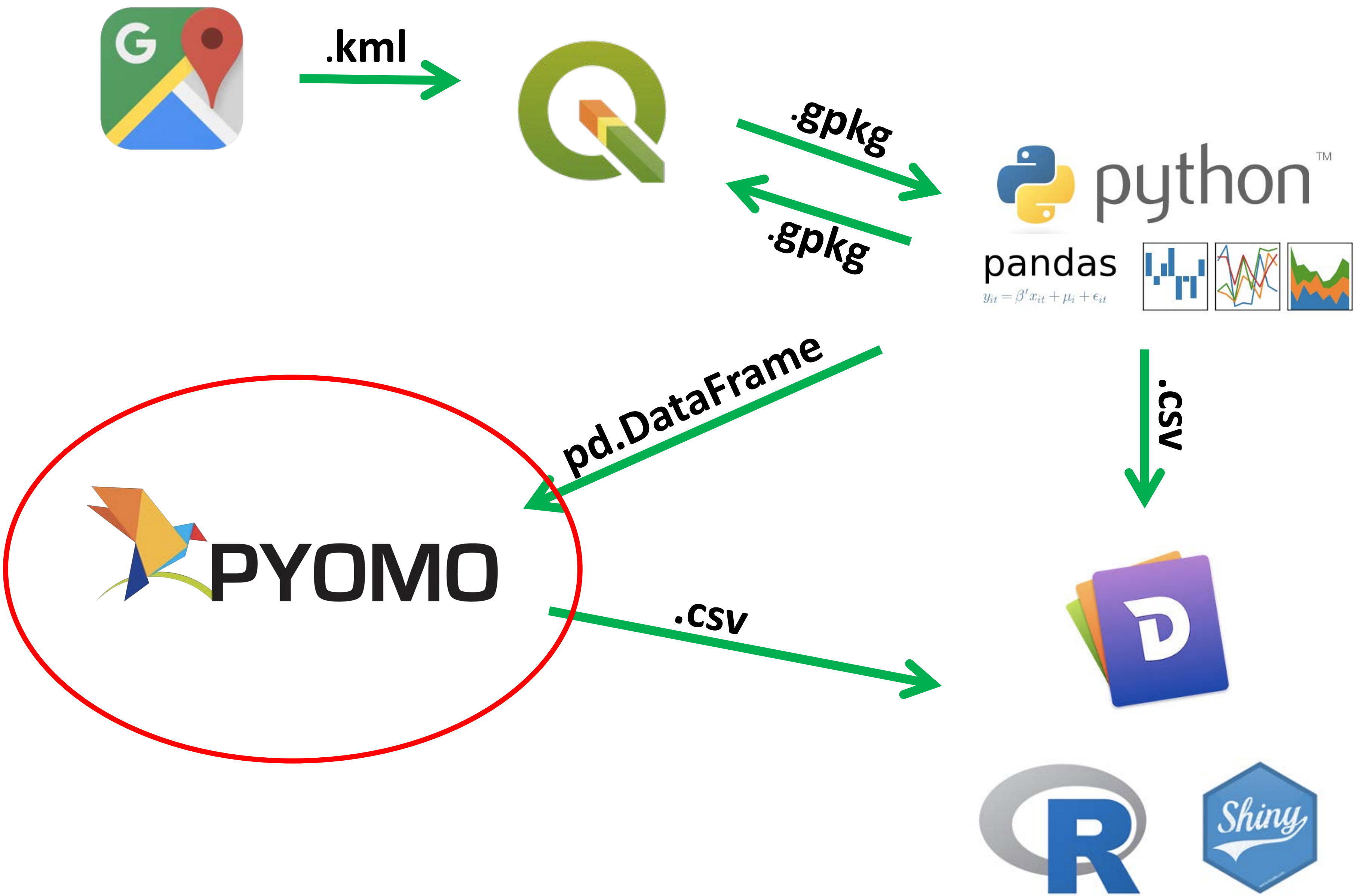
- Incorrect per-unit voltage for infrastructure
- Recirculation issues (mislabeled delta & wye transformers)
- Customers outside normal voltage constraints

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


.kml
.gpkg
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pandas
$y_{it} = \beta' x_{it} + \mu_i + \epsilon_{it}$
pd.DataFrame
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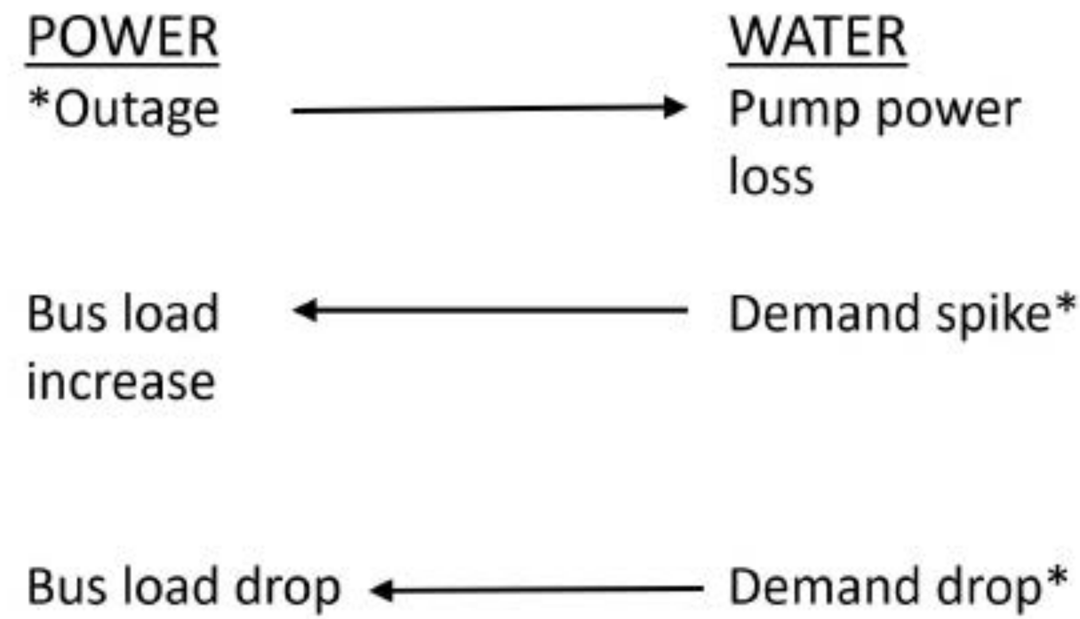
Interdependent Water-Power Failure Simulation



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

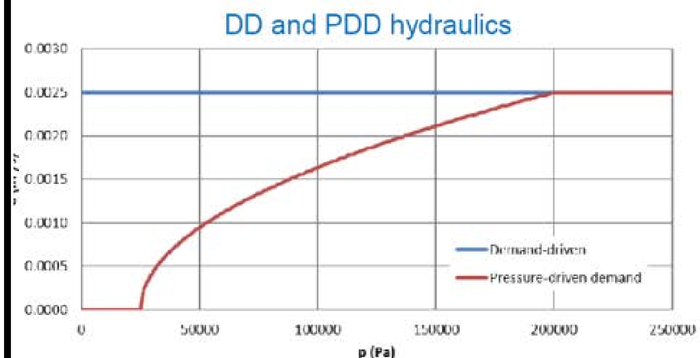
Bunn BB, 2018, **“An Operational Model of Interdependent Water and Power Distribution Infrastructure Systems,”** M.S. Thesis in Operations Research, Naval Postgraduate School, Monterey, CA.

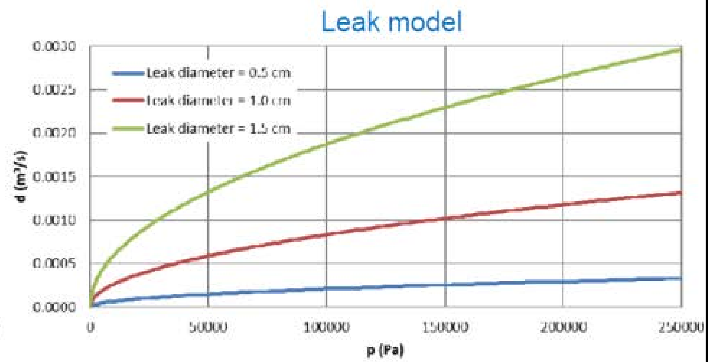
Pyomo Models for Water & Electricity Distribution

Simulation engines

- 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	✓





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

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

9

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

Pyomo Models for Water & Electricity Distribution

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	DD Hydraulics	PDD Hydraulics	Water quality
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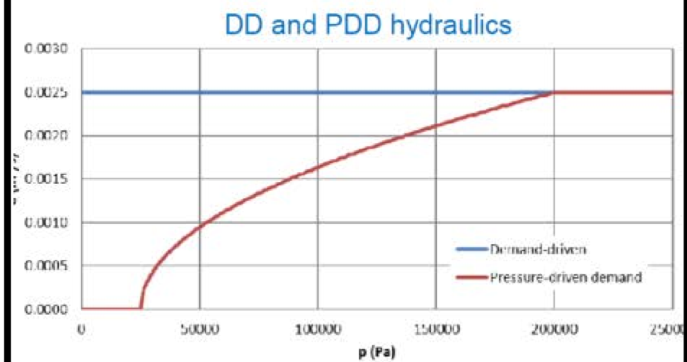

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Approved for public release. Distribution is unlimited.

ASSESSING THE OPERATIONAL RESILIENCE OF ELECTRICAL DISTRIBUTION SYSTEMS

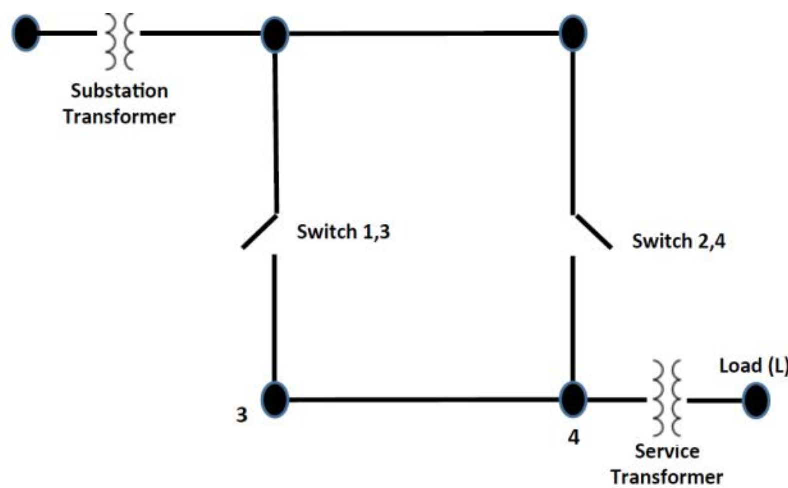
Clark Petri
Lieutenant Commander, United States Navy
B.S., Oregon State University, 2005

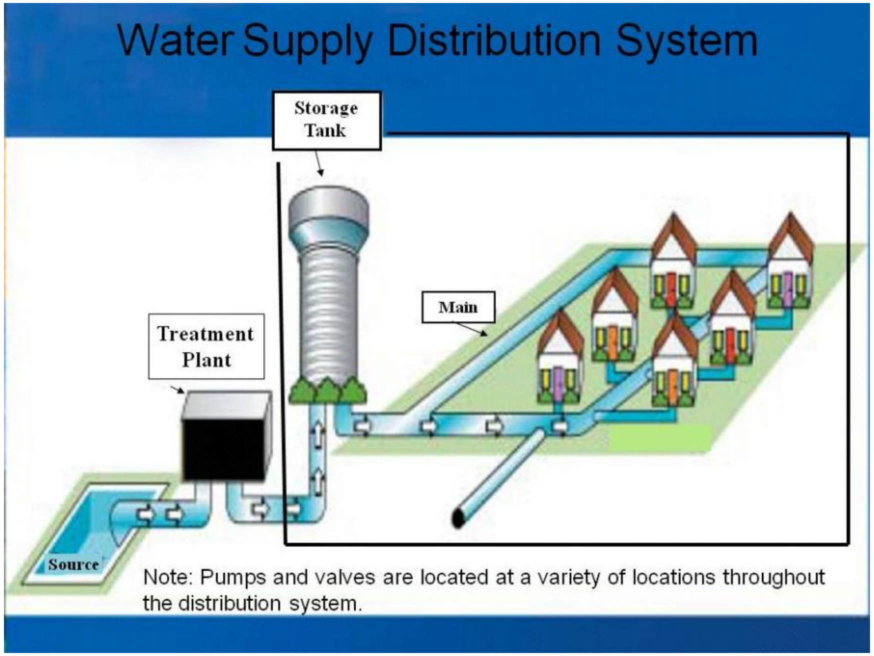
Submitted in partial fulfillment of the requirements for the degree of

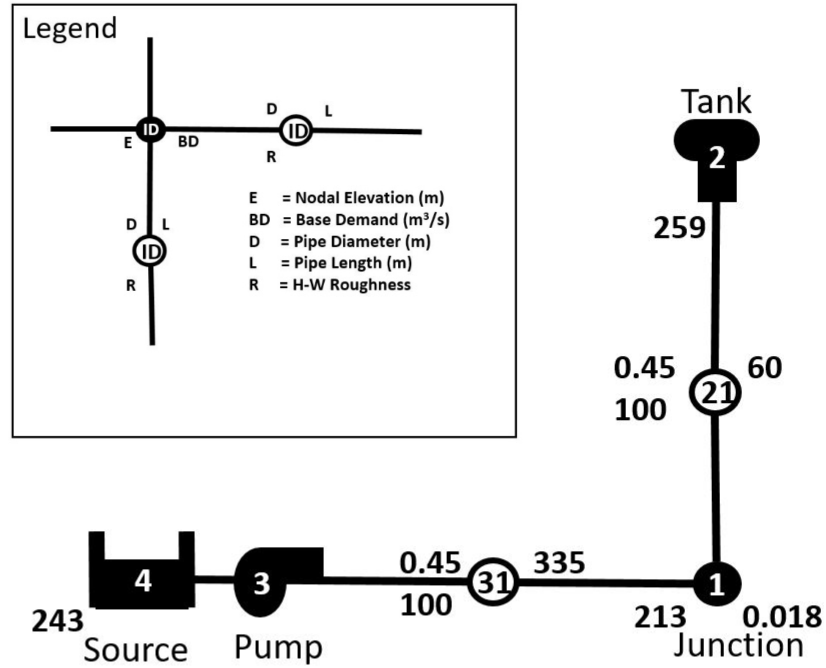
MASTER OF SCIENCE IN OPERATIONS RESEARCH

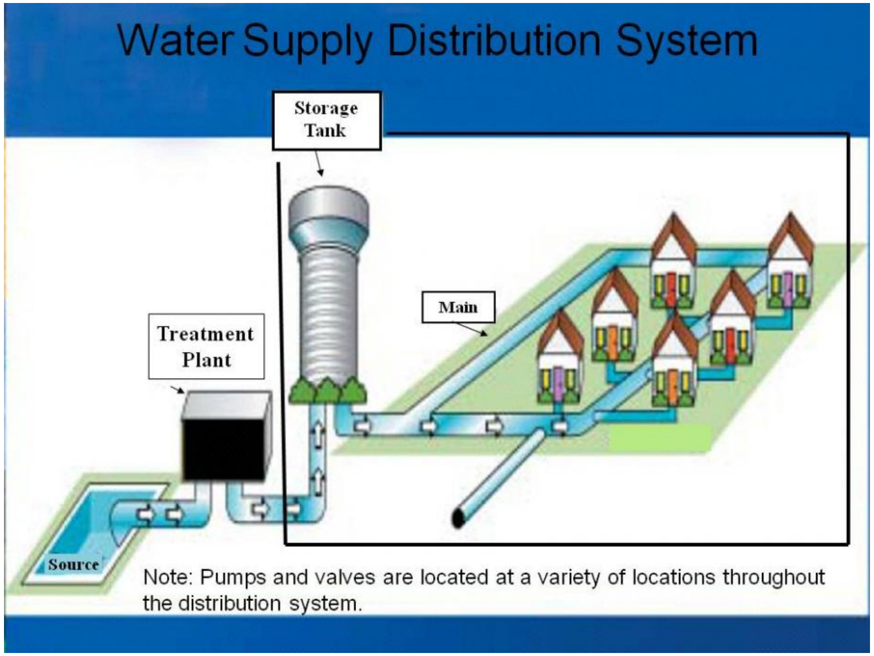
from the

NAVAL POSTGRADUATE SCHOOL
September 2017




Water Supply Distribution System
Storage Tank
Main
Treatment Plant
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
60
21
100
4
3
0.45
31
335
1
100
243
213
0.018
Source
Pump
Junction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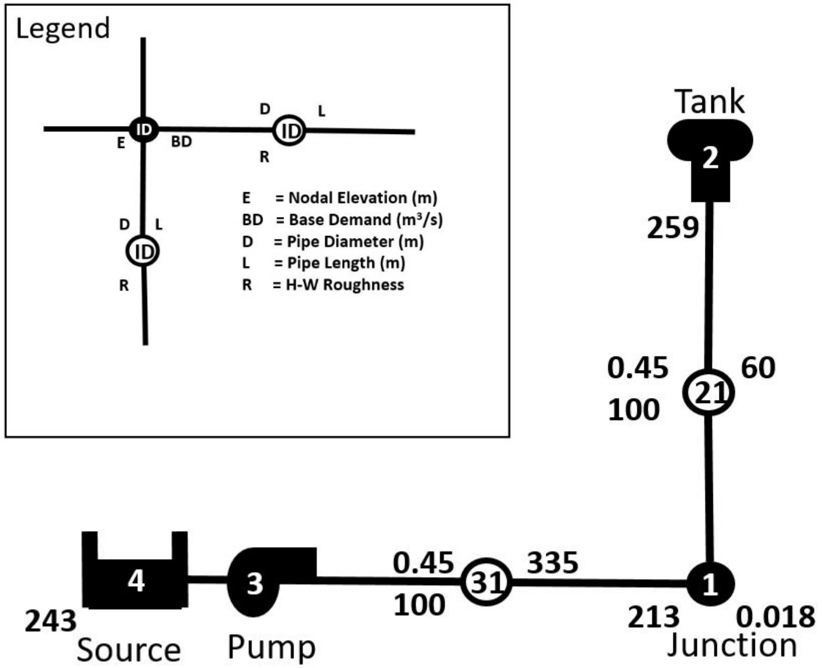
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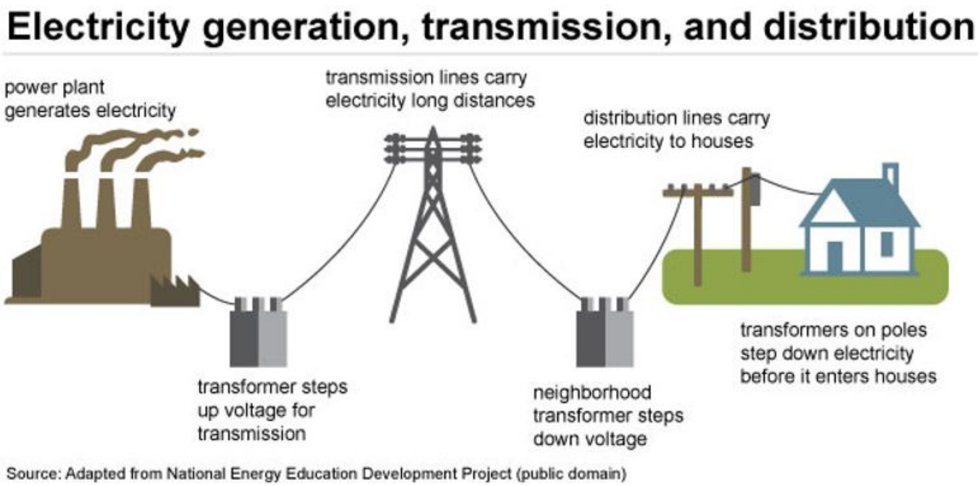
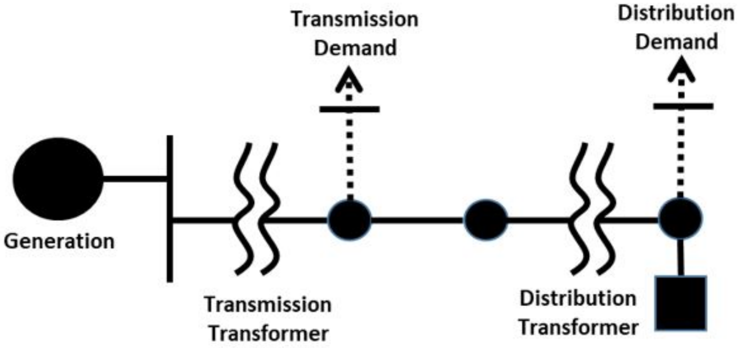
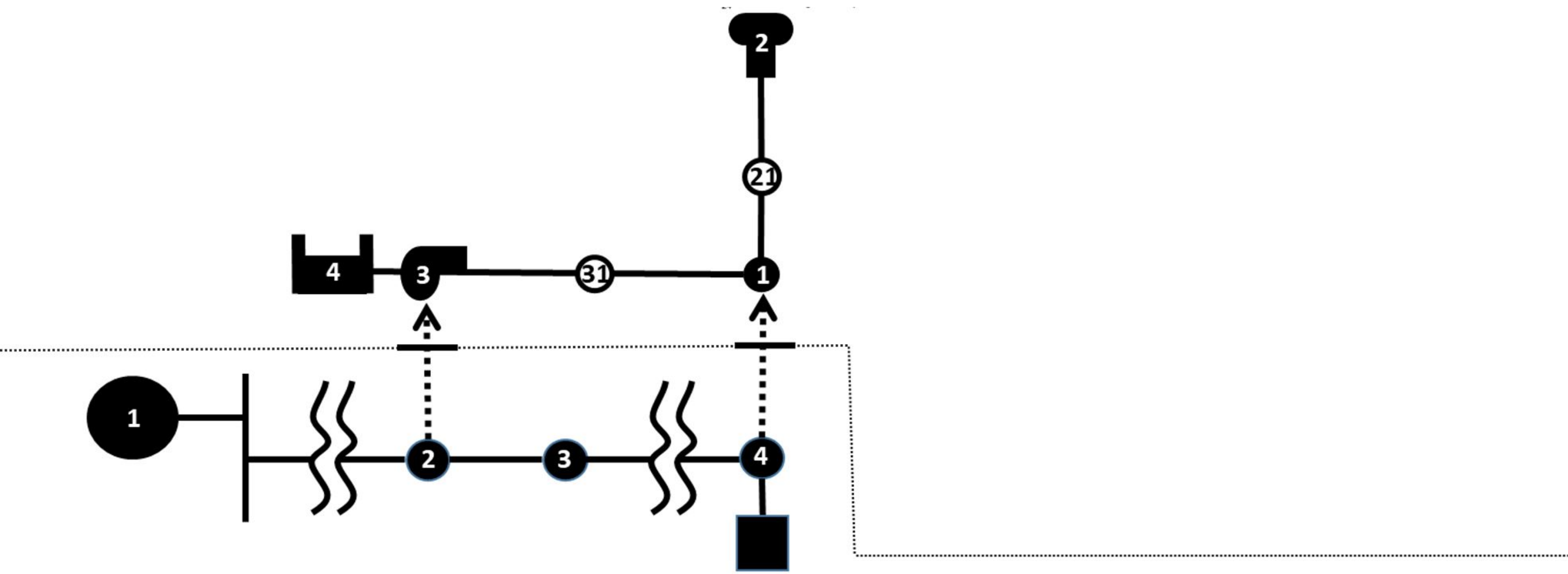
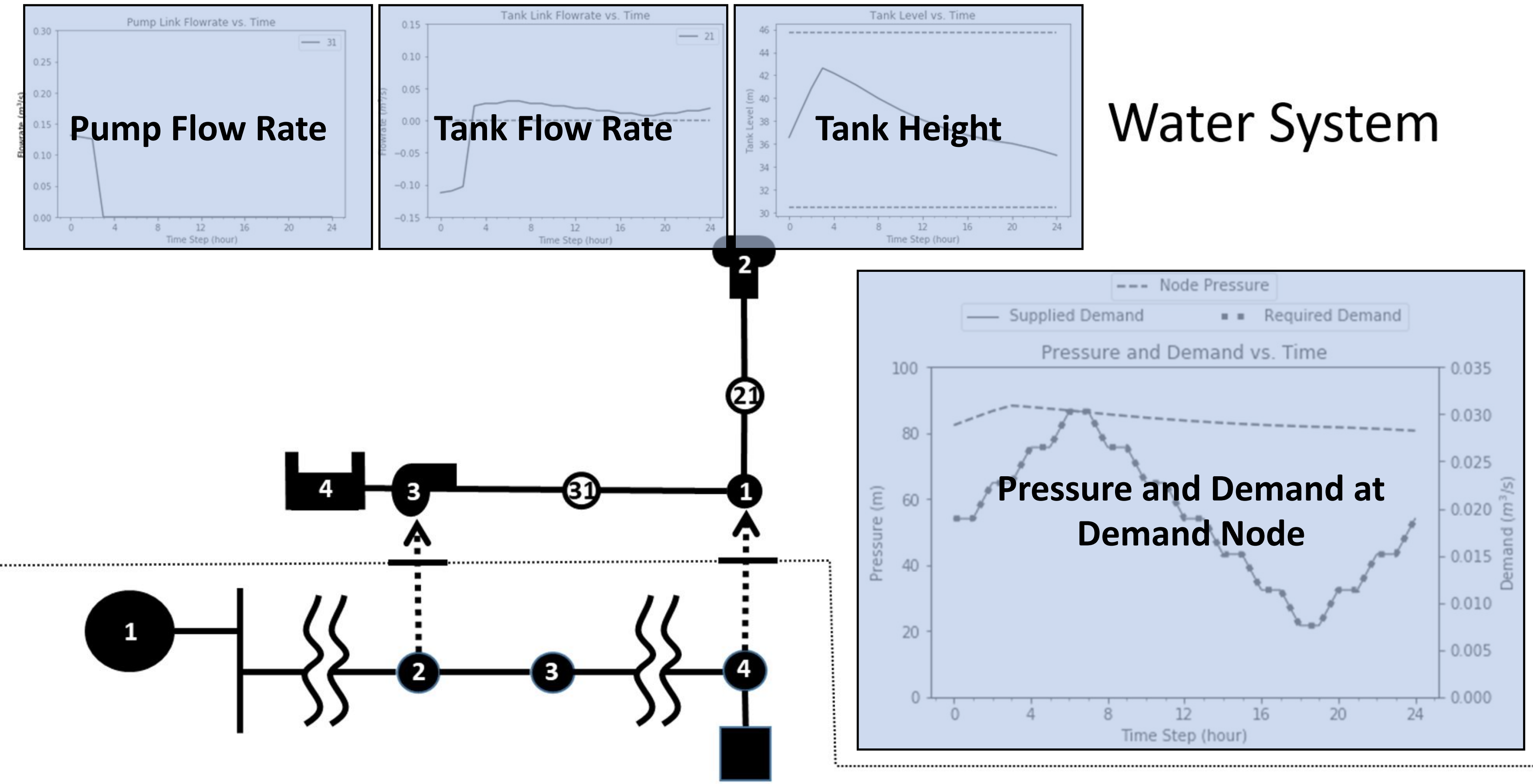

Electricity generation, transmission, and distribution
power plant generates electricity
transmission lines carry electricity long distances
distribution lines carry electricity to houses
transformer steps up voltage for transmission
neighborhood transformer steps down voltage
transformers on poles step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


Transmission Demand
Distribution Demand
Generation
Transmission Transformer
Distribution Transformer

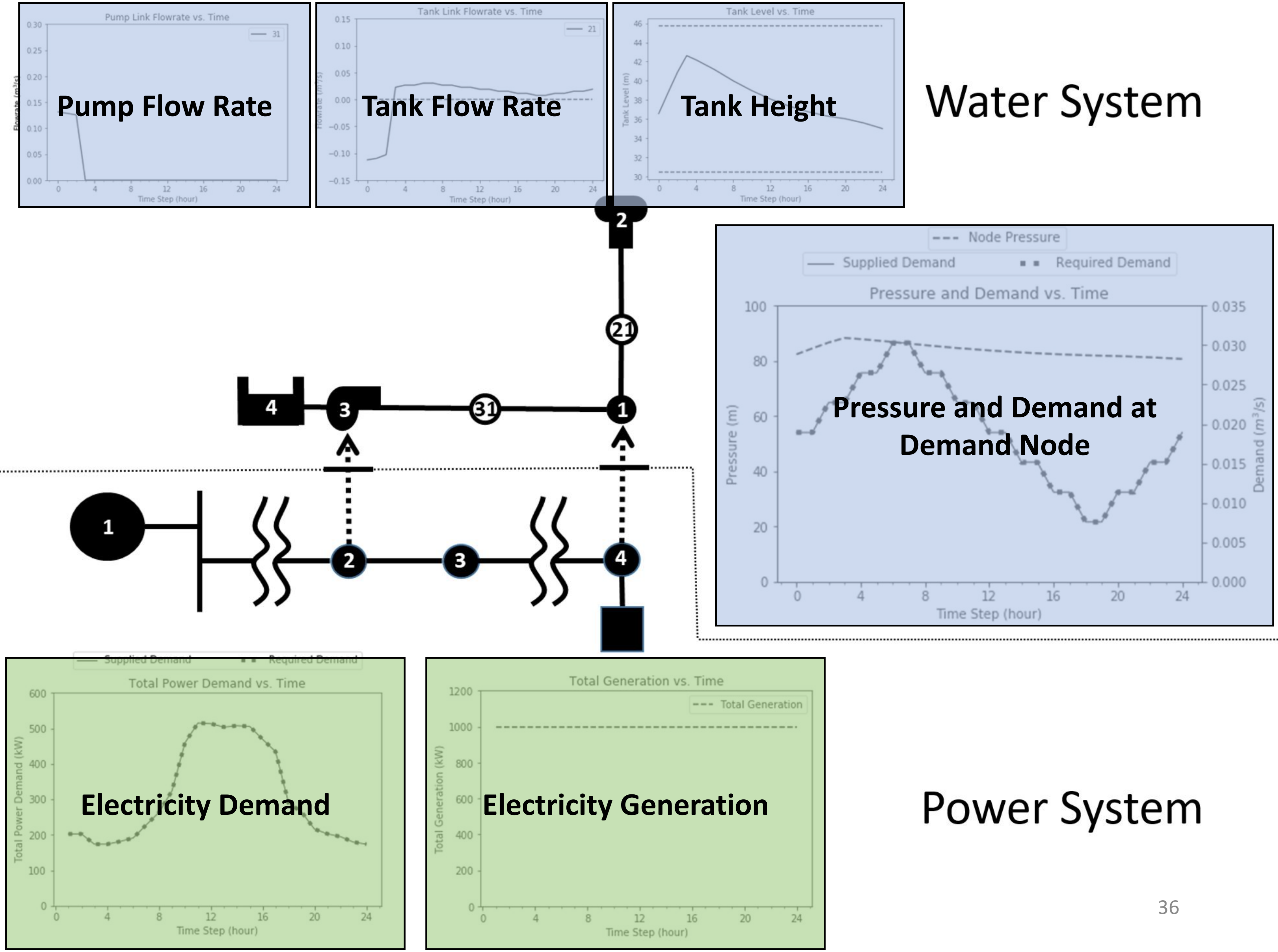
Water System

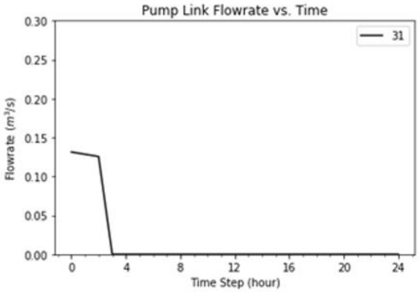


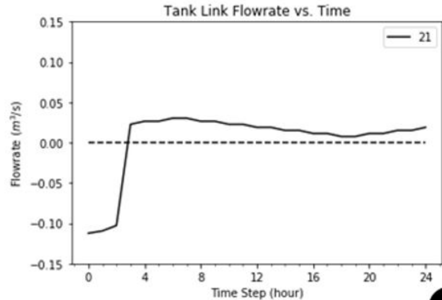
Power System

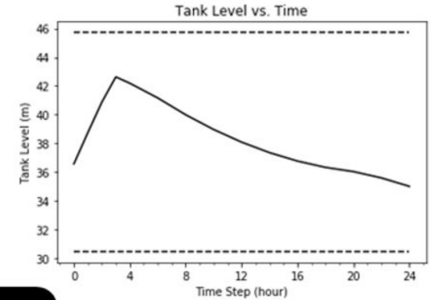


Power System

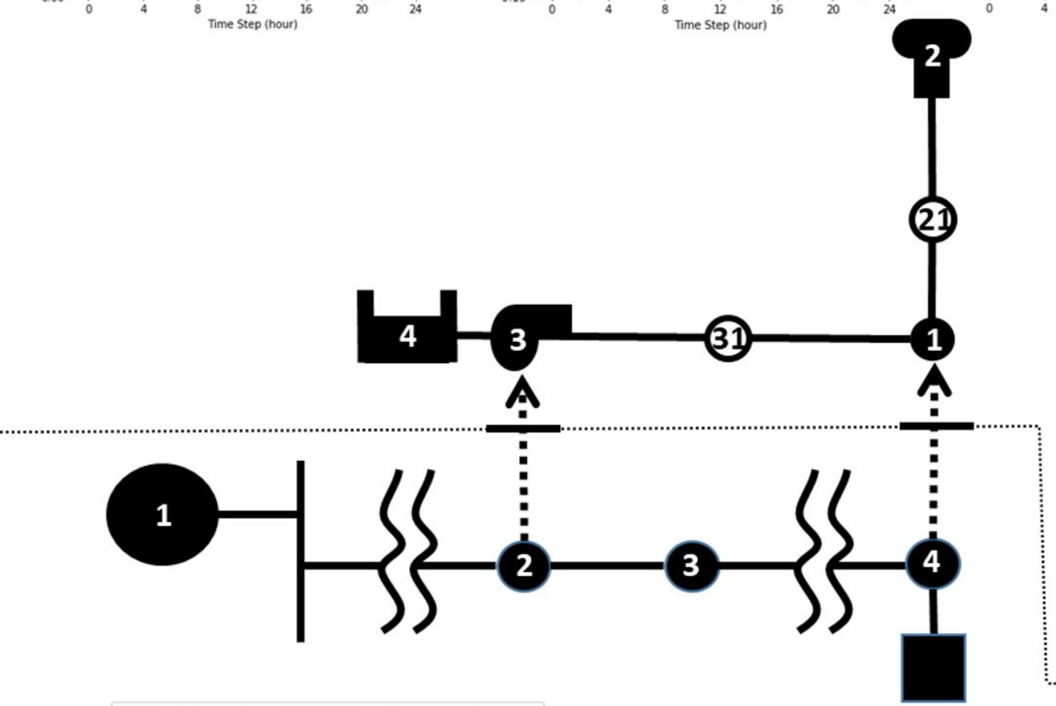

Pump Flow Rate
Pump Link Flowrate vs. Time
Tank Flow Rate
Tank Link Flowrate vs. Time
Tank Height
Tank Level vs. Time
Water System
Node Pressure
Supplied Demand
Required Demand
Pressure and Demand vs. Time
Pressure and Demand at Demand Node
Pressure (m)
Time Step (hour)
Total Power Demand vs. Time
Electricity Demand
Total Power Demand (kW)
Total Generation vs. Time
Total Generation
Electricity Generation
Total Generation (kW)
Power System

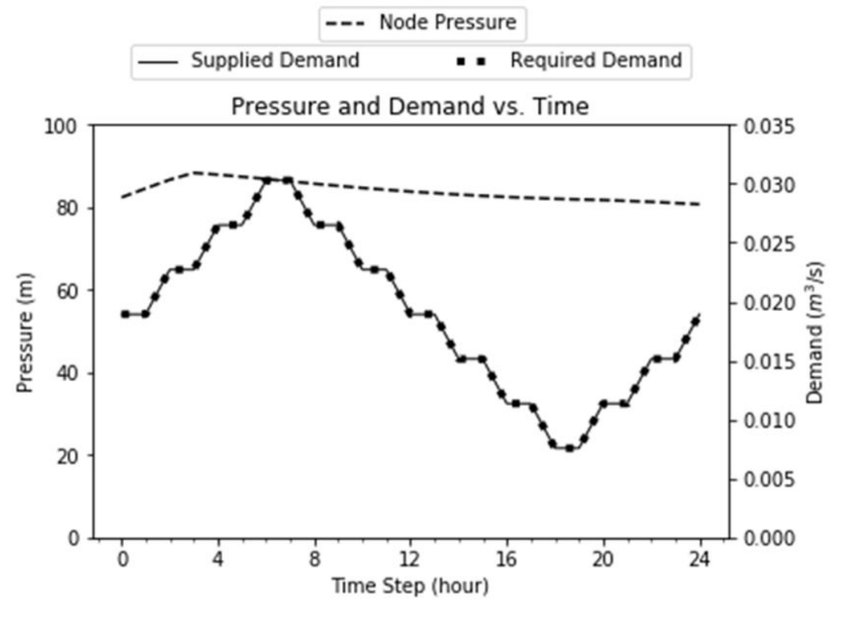


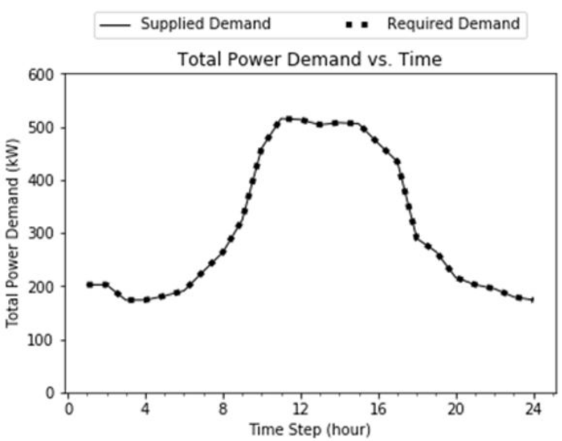


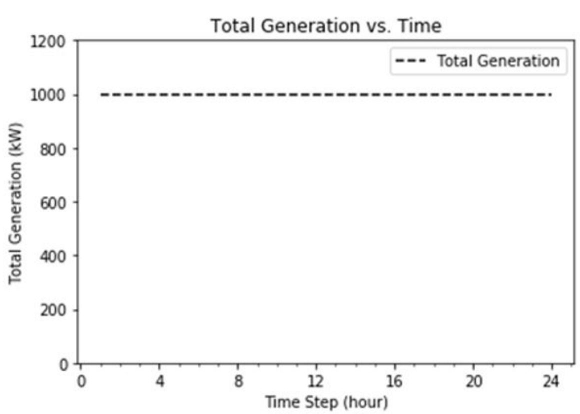


Water System

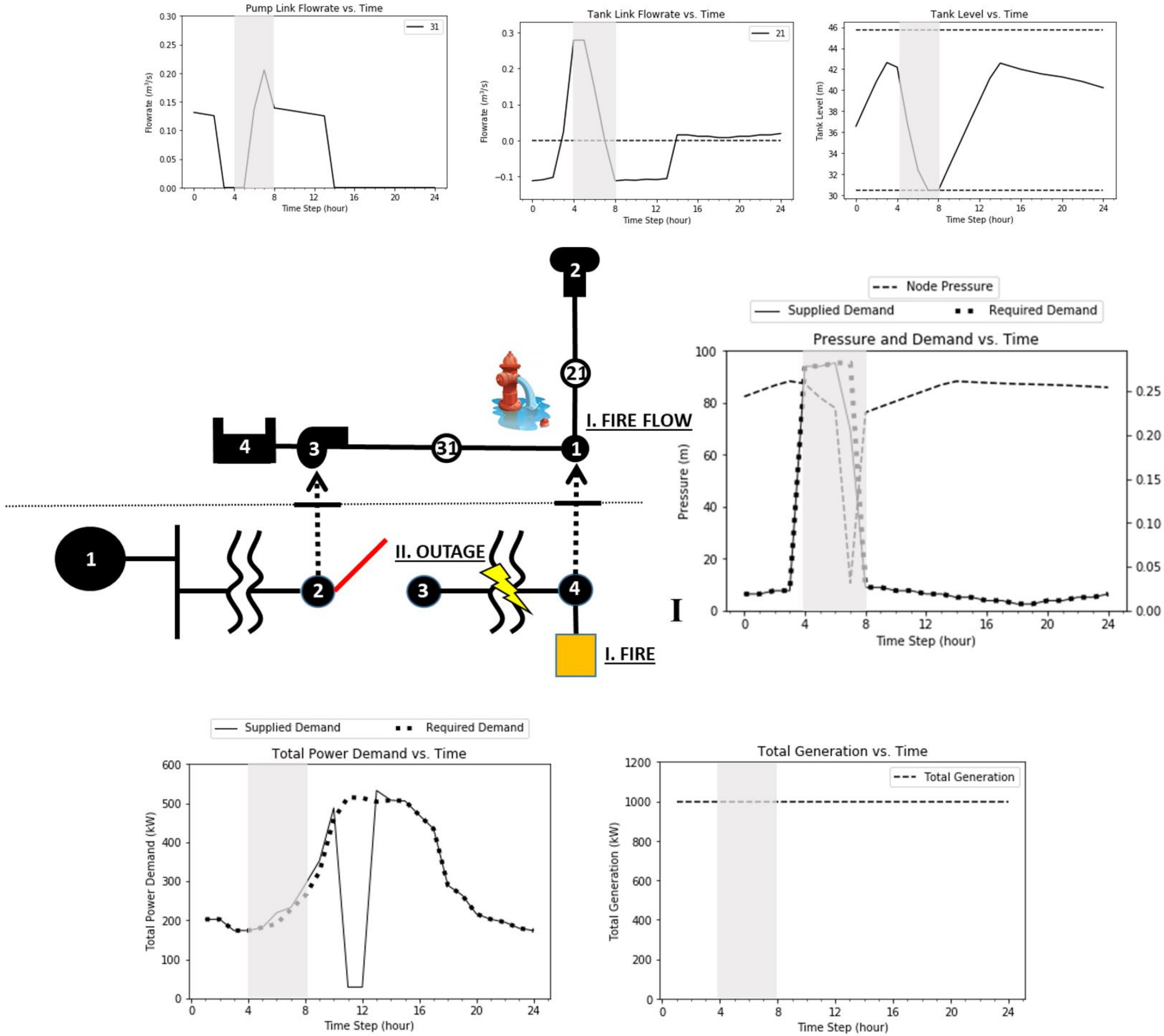






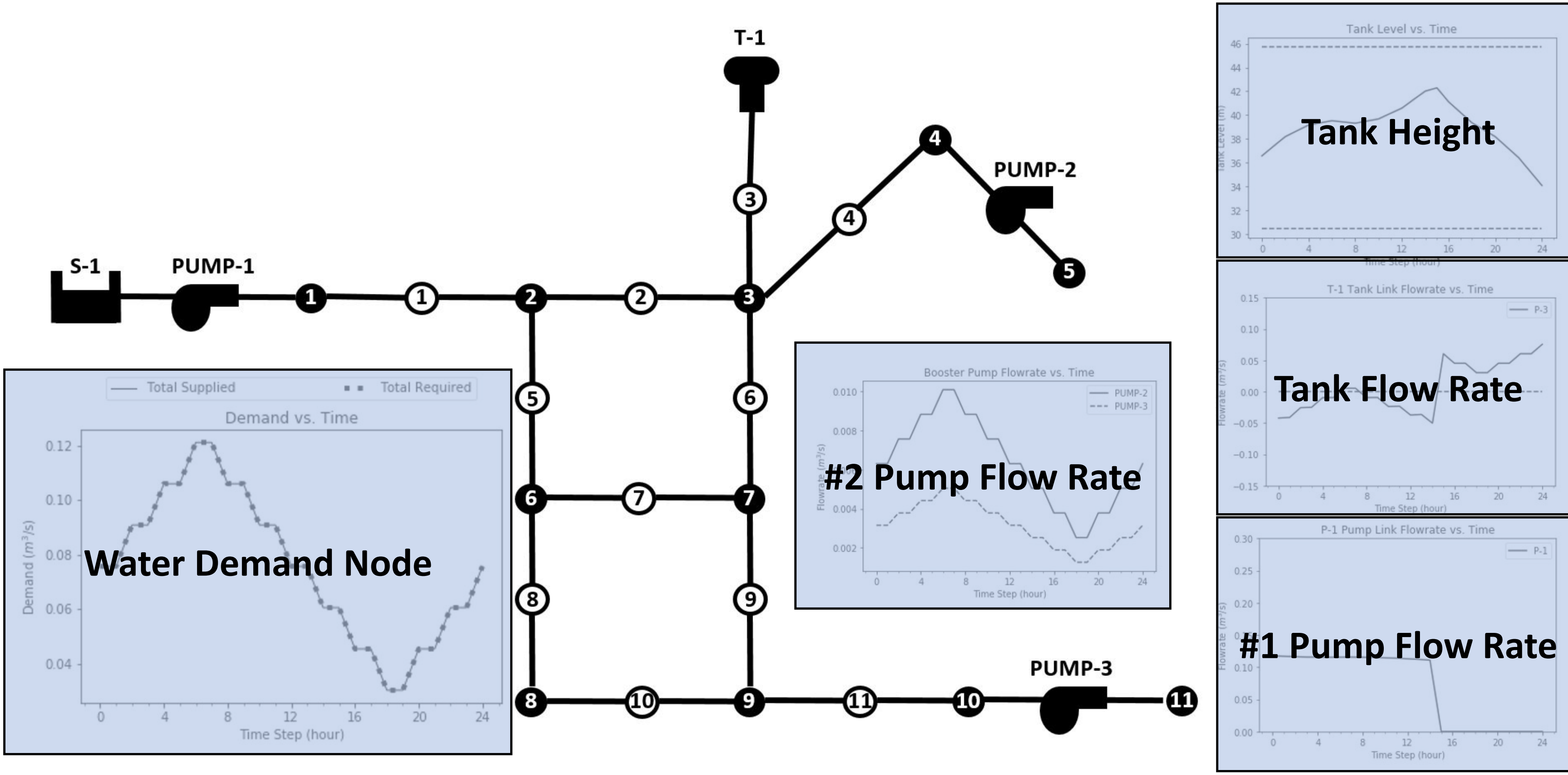


Power System

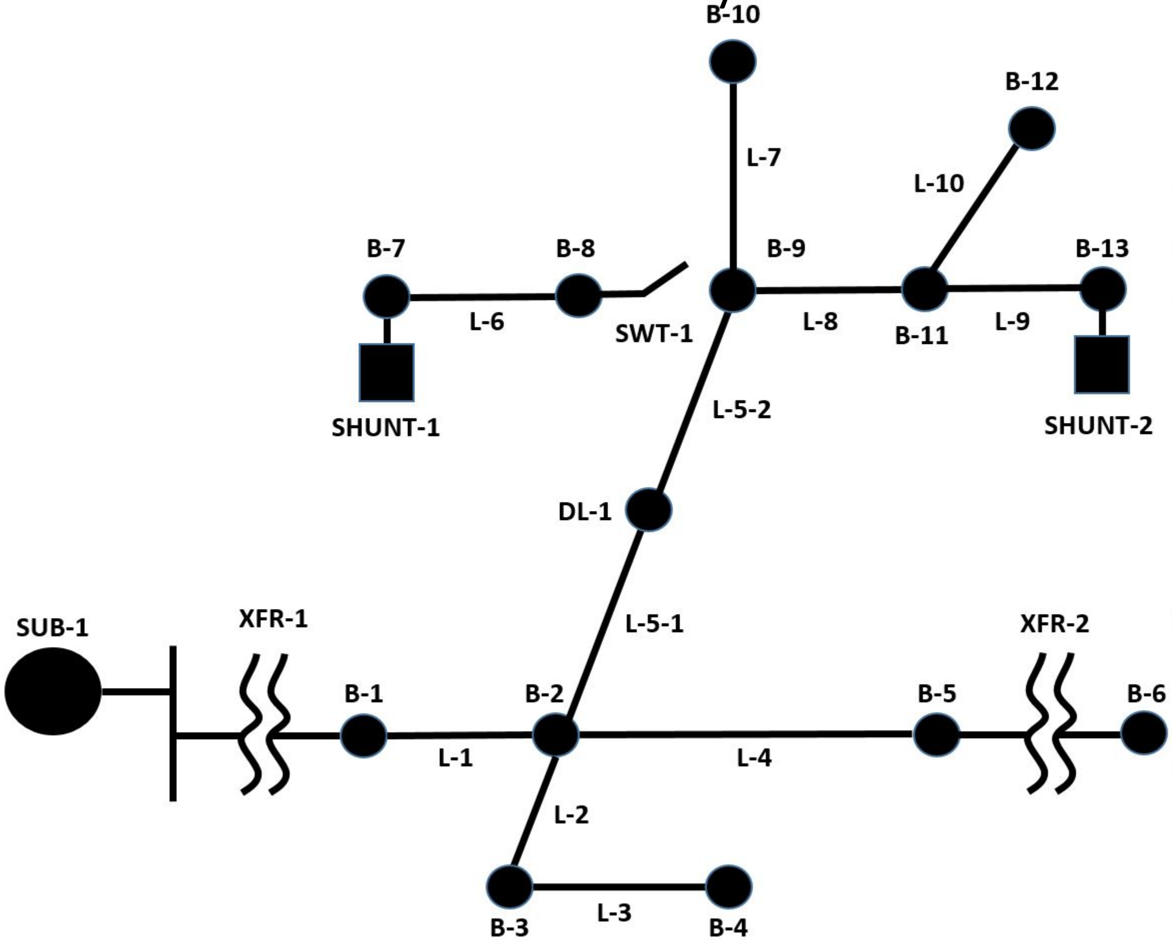


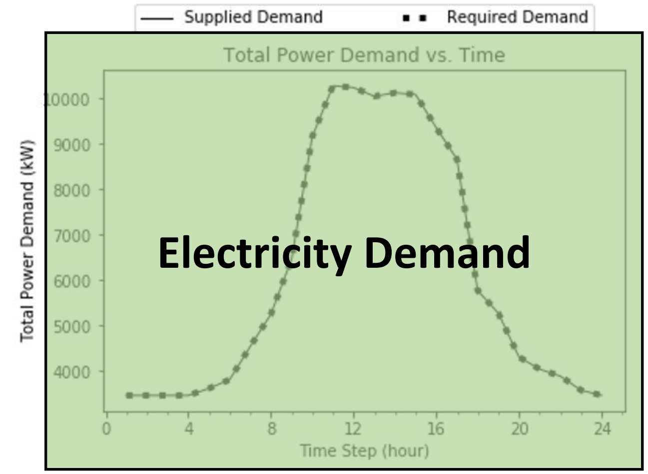
Pump Link Flowrate vs. Time
Flowrate (m^3/s)
Time Step (hour)
31
Tank Link Flowrate vs. Time
21
Tank Level vs. Time
Tank Level (m)
I. FIRE FLOW
II. OUTAGE
I. FIRE
Node Pressure
Supplied Demand
Required Demand
Pressure and Demand vs. Time
Pressure (m)
Demand (m^3/s)
Total Power Demand vs. Time
Total Power Demand (kW)
Total Generation vs. Time
Total Generation
Total Generation (kW)

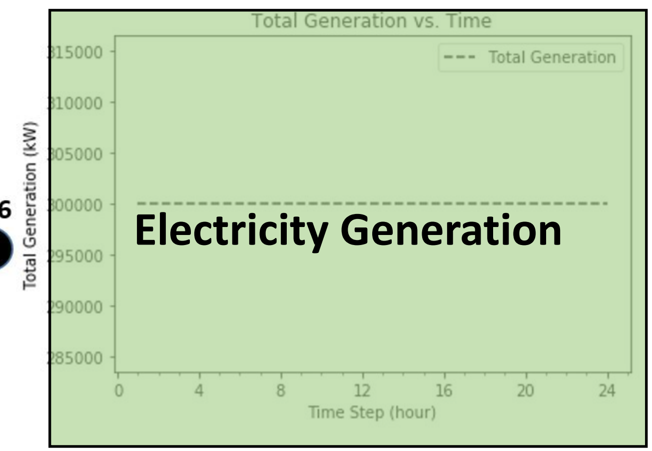
A more realistic (USVI) water distribution system

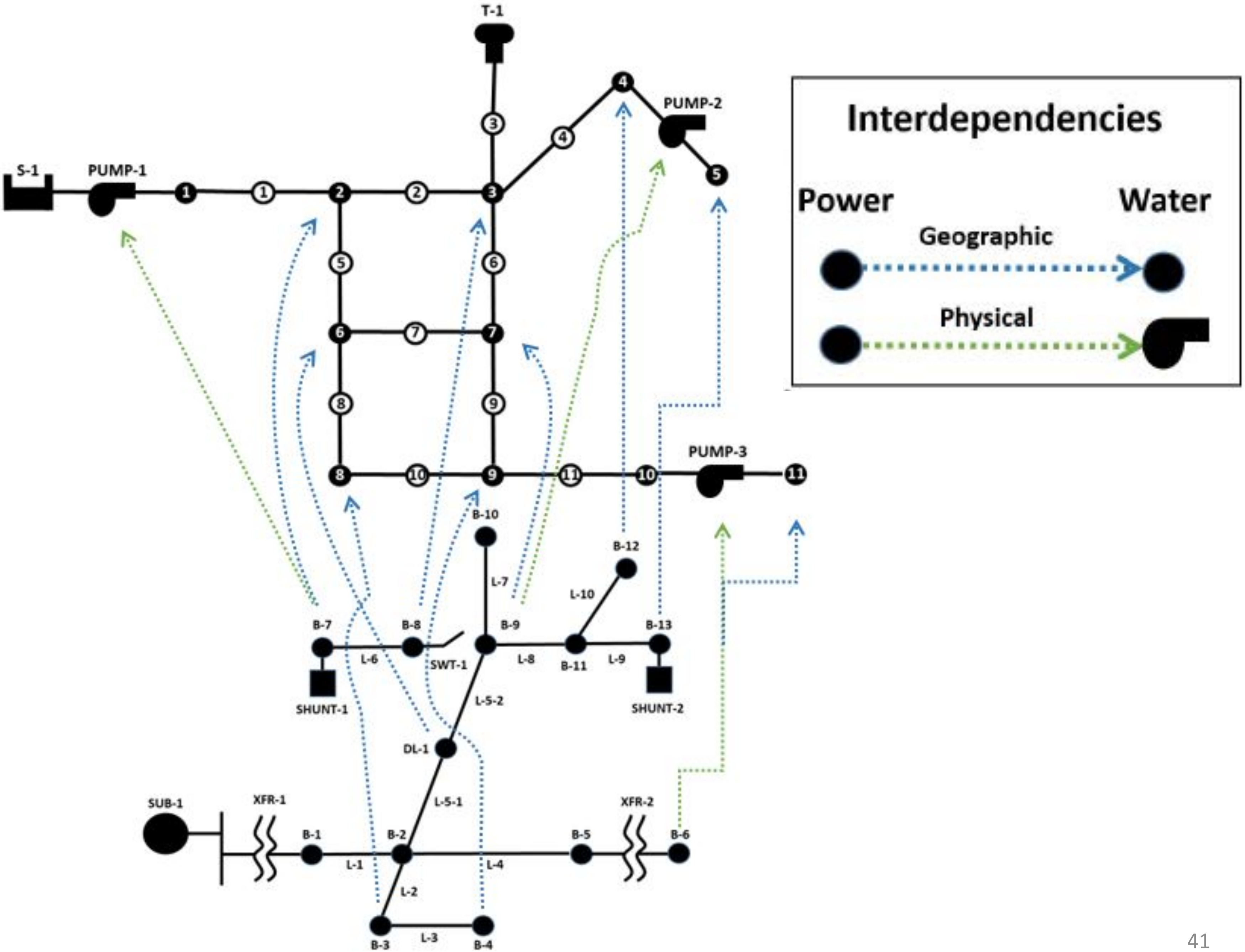


IEEE 13-bus electricity distribution network

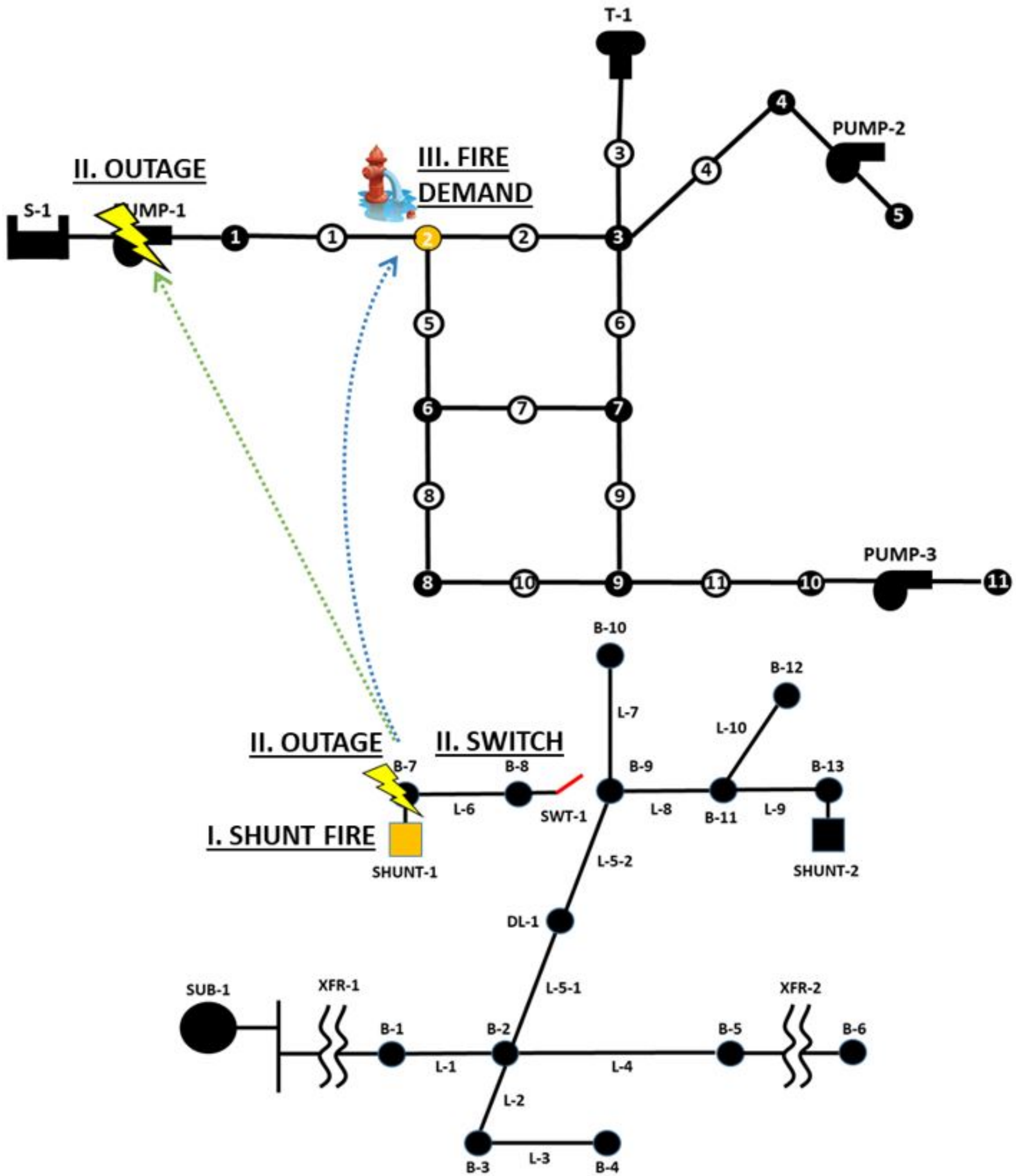


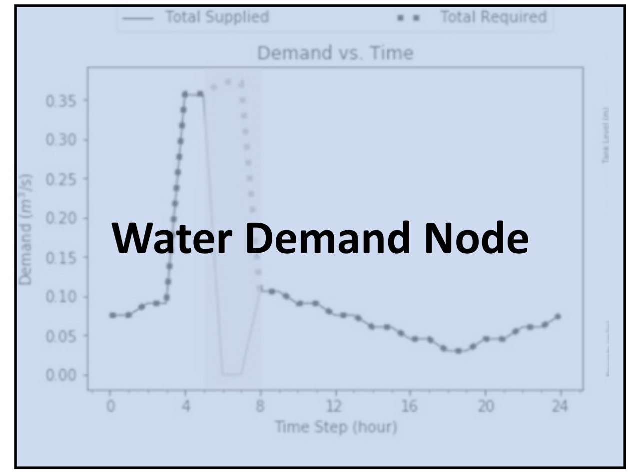


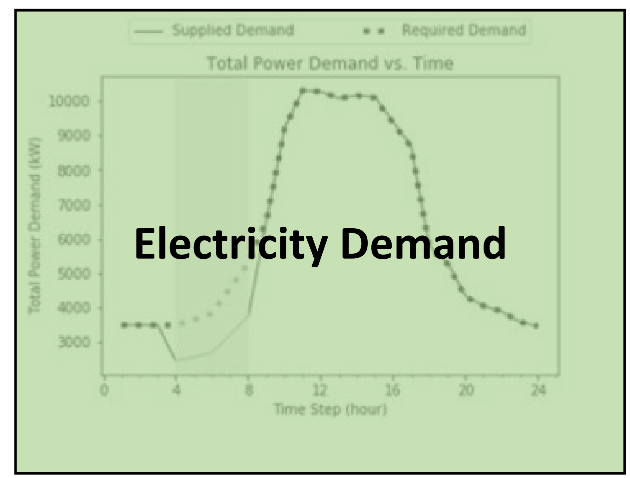


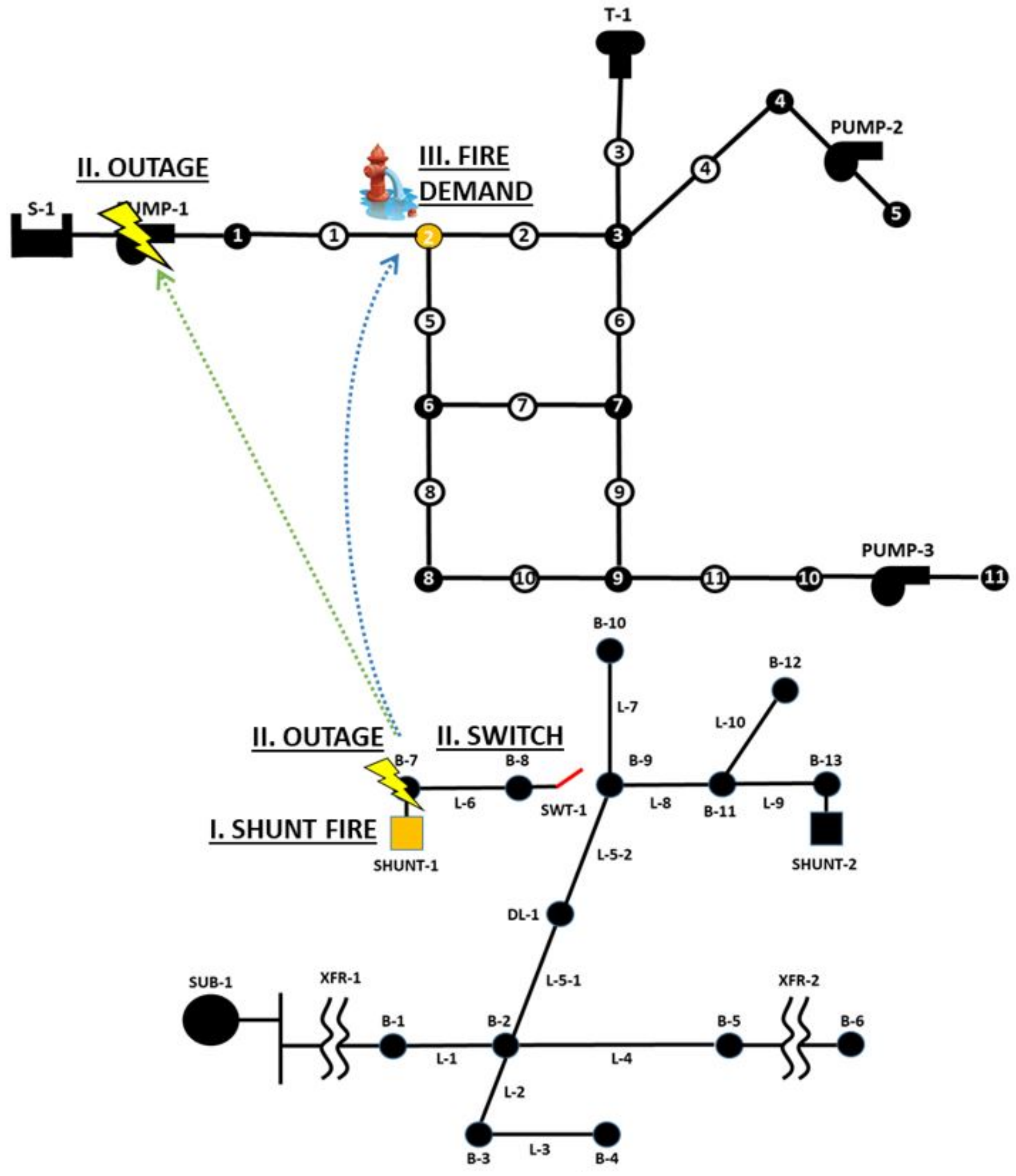


T-1
PUMP-2
S-1
PUMP-1
PUMP-3
B-10
B-12
L-7
L-10
B-7
B-8
B-9
B-13
L-6
SWT-1
L-8
B-11
L-9
SHUNT-1
L-5-2
SHUNT-2
DL-1
SUB-1
XFR-1
L-5-1
XFR-2
B-1
B-2
B-5
B-6
L-1
L-4
L-2
B-3
L-3
B-4
Interdependencies
Power
Water
Geographic
Physical

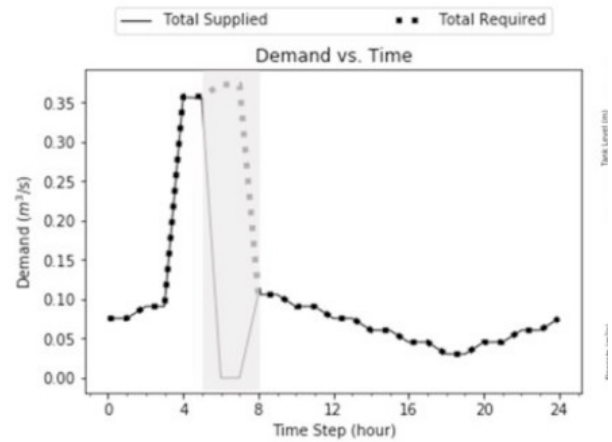

T-1
PUMP-2
II. OUTAGE
III. FIRE DEMAND
S-1
PUMP-1
PUMP-3
B-10
B-12
L-7
L-10
II. OUTAGE
II. SWITCH
B-7
B-8
B-9
B-13
L-6
SWT-1
L-8
B-11
L-9
I. SHUNT FIRE
SHUNT-1
SHUNT-2
L-5-2
DL-1
L-5-1
SUB-1
XFR-1
XFR-2
B-1
B-2
B-5
B-6
L-1
L-4
L-2
B-3
L-3
B-4


Total Supplied
Total Required
Demand vs. Time
Water Demand Node
Time Step (hour)

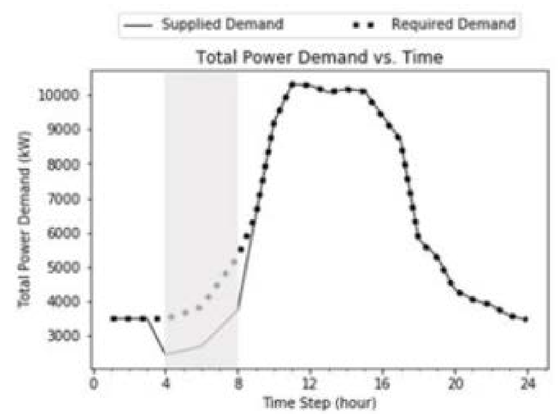

Supplied Demand
Required Demand
Total Power Demand vs. Time
Electricity Demand
Time Step (hour)



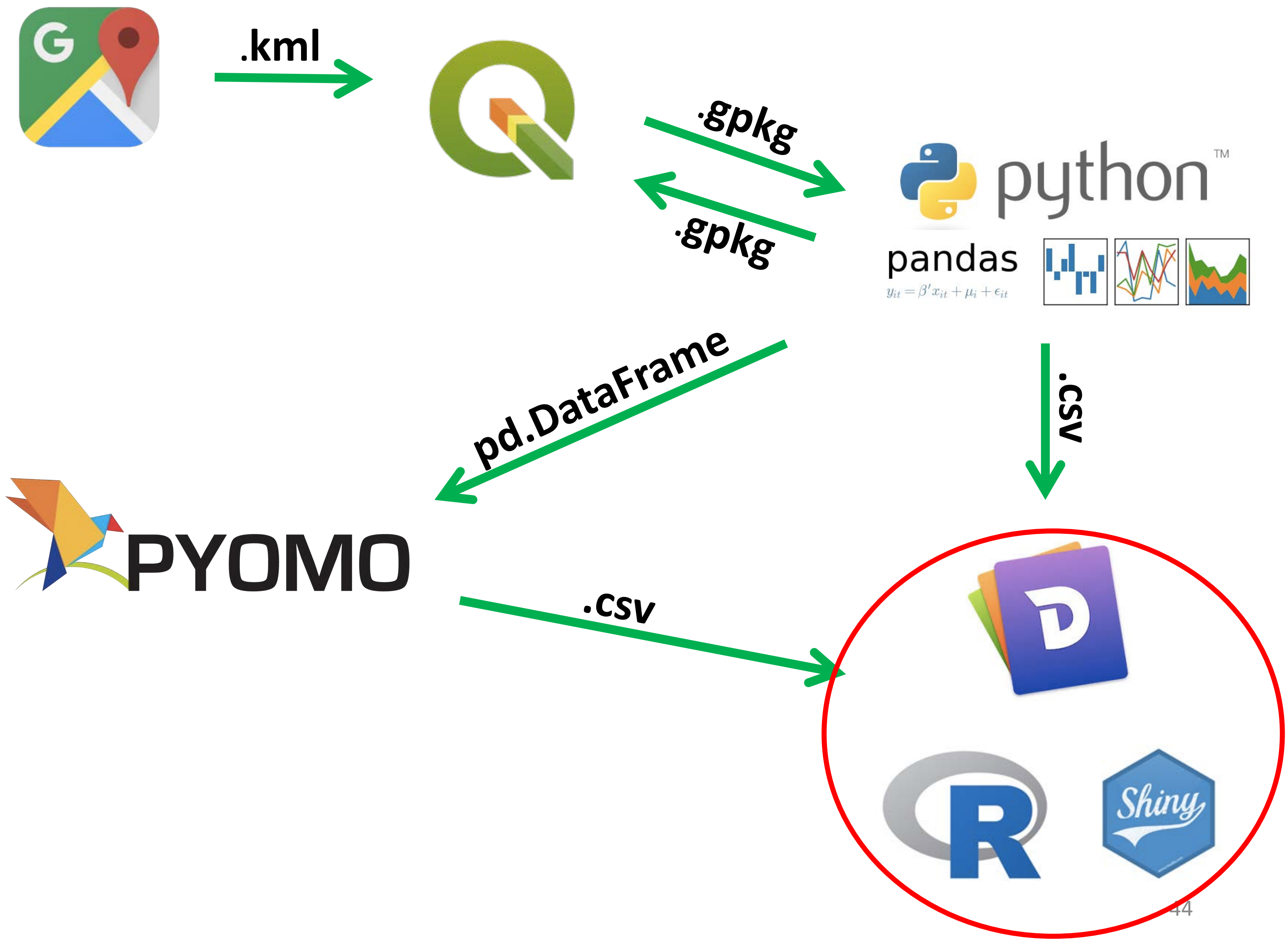
T-1
PUMP-2
II. OUTAGE
III. FIRE DEMAND
S-1
PUMP-1
PUMP-3
B-10
B-12
L-7
L-10
II. OUTAGE
II. SWITCH
B-7
B-8
B-9
B-13
L-6
SWT-1
L-8
B-11
L-9
I. SHUNT FIRE
SHUNT-1
SHUNT-2
L-5-2
DL-1
L-5-1
SUB-1
XFR-1
XFR-2
B-1
B-2
B-5
B-6
L-1
L-4
L-2
L-3
B-3
B-4



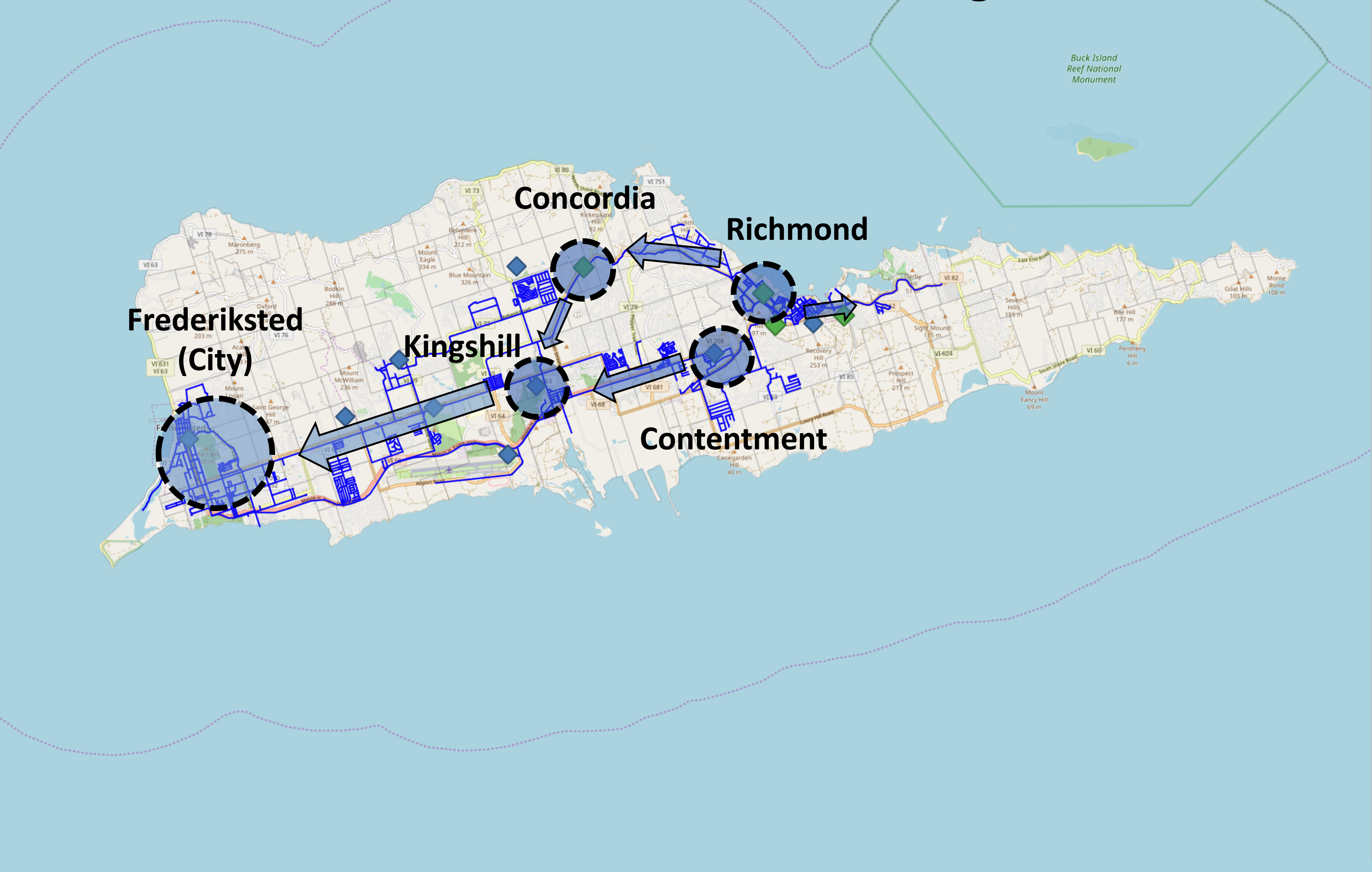
Total Supplied
Total Required
Demand vs. Time
Demand (m^3/s)
Time Step (hour)



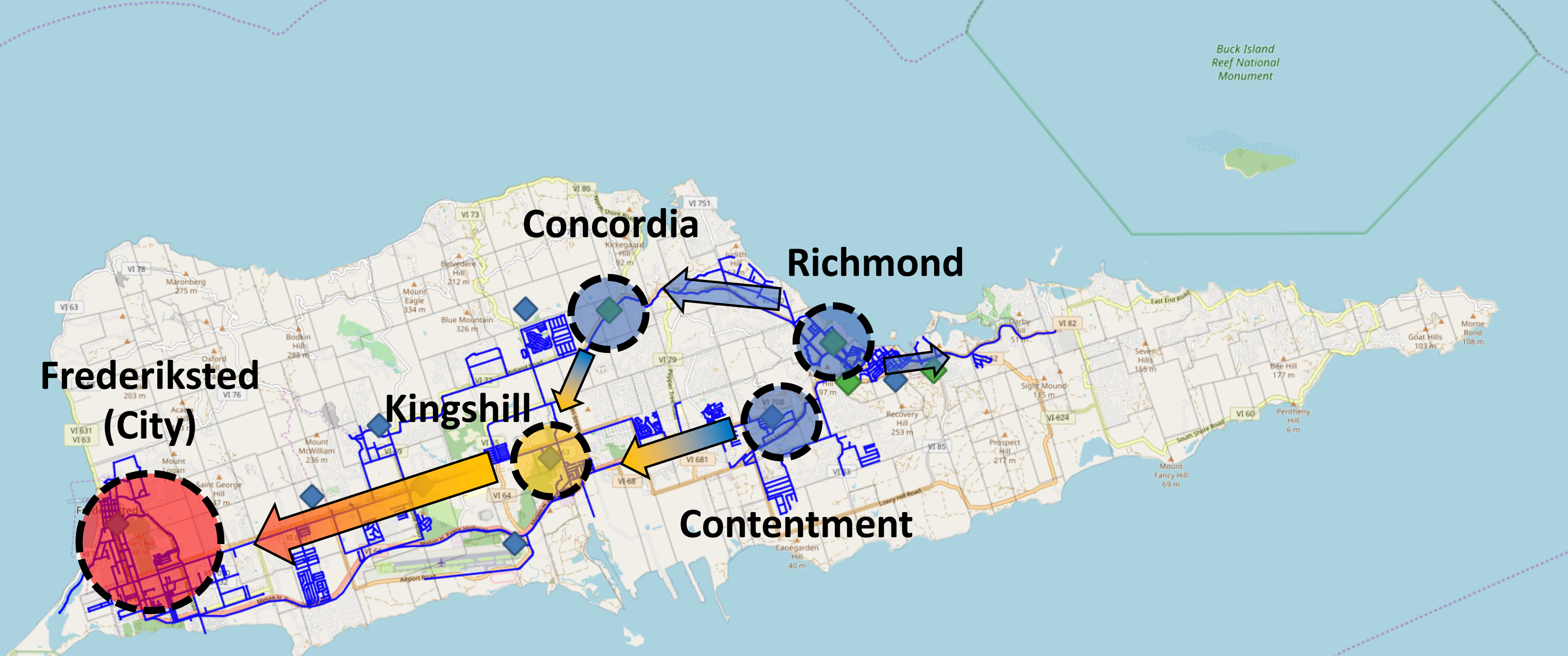
Supplied Demand
Required Demand
Total Power Demand vs. Time
Total Power Demand (kW)
Time Step (hour)


.kml
.gpkg
.gpkg
python
pandas
$y_{it} = \beta' x_{it} + \mu_i + \epsilon_{it}$
pd.DataFrame
.csv
PYOMO
.csv
Shiny

Current Goals: Setting a Baseline Through Past Events March 2019 STX West Coast Water Outages



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:

- 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

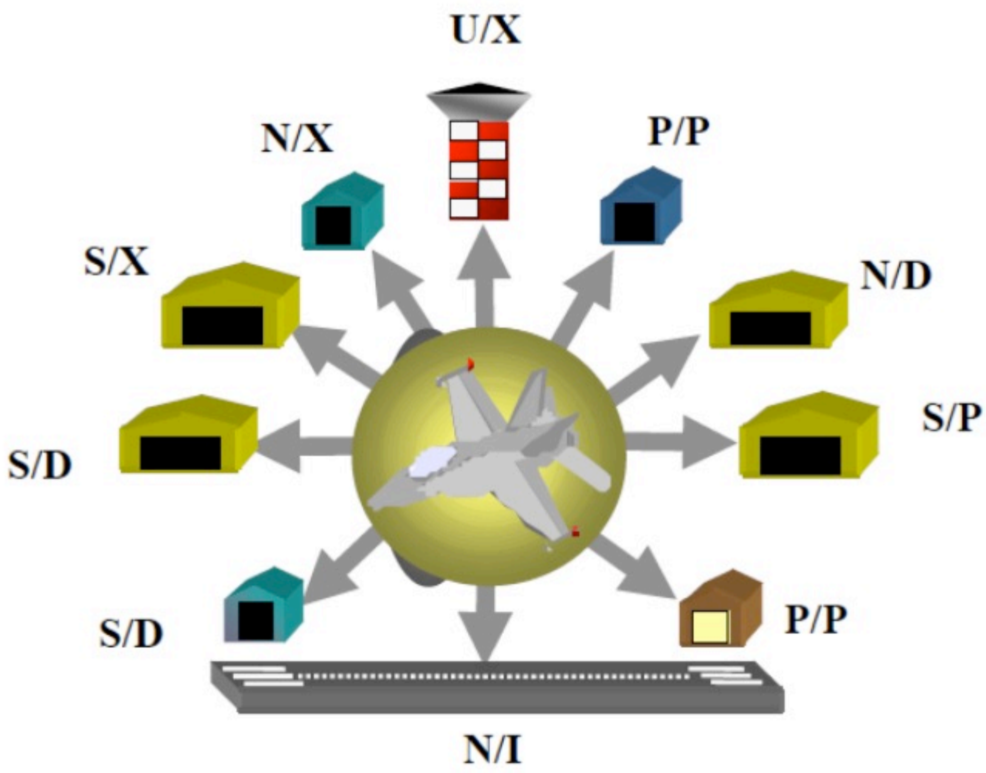
Backup Slides

The Mission Dependency Index

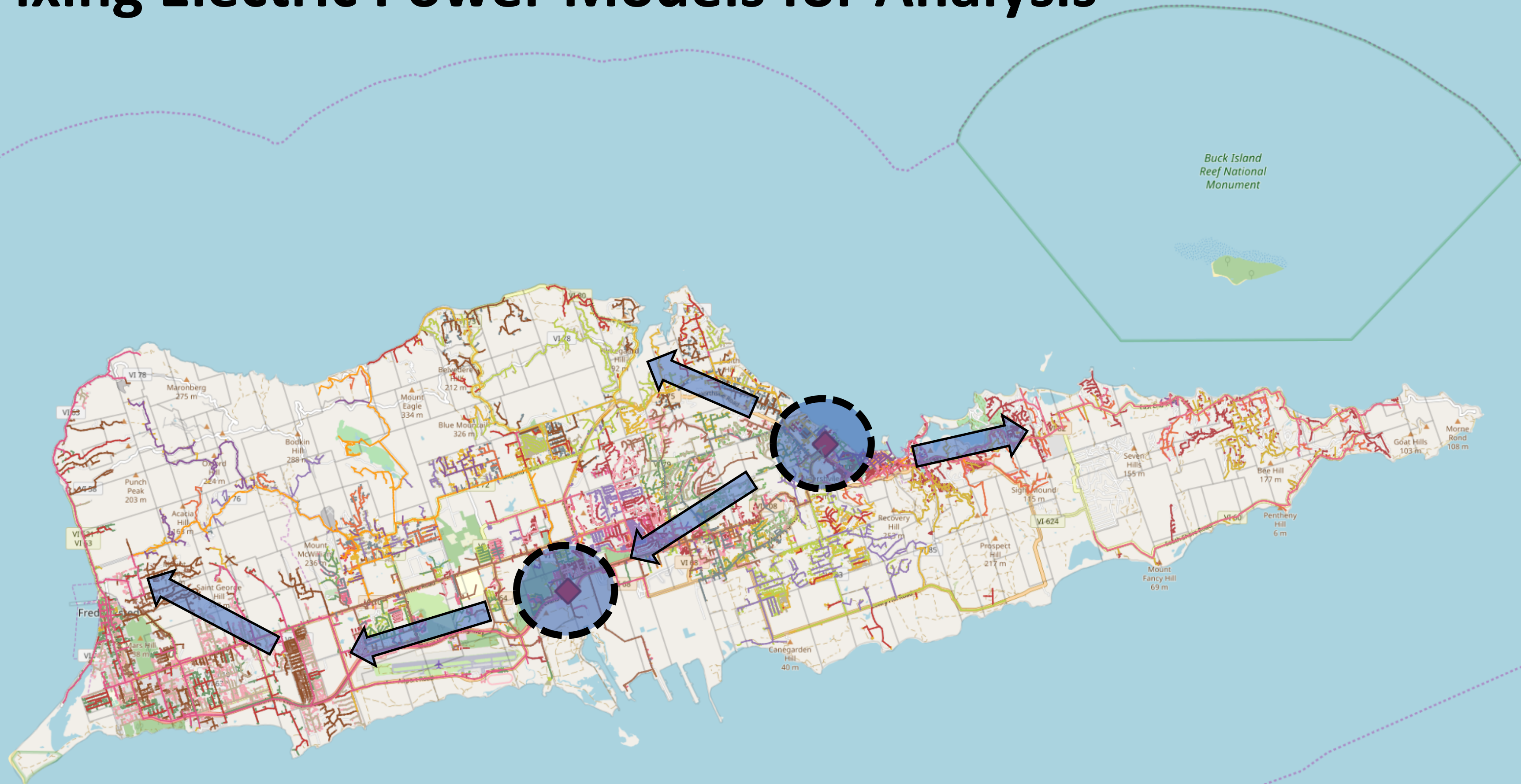
Antelman, A. (2008). *United States Air Force Mission Dependency Index (MDI) Proof of Concept Report*. Port Hueneme, California: Naval Facilities Engineering Service Center.

Interruptibility Score
None (N)
Urgent (U)
Brief (B)
Short (S)
Prolonged (P)

Relocatability / Replaceability Score
Impossible (I)
Extremely Difficult (X)
Difficult (D)
Possible (P)



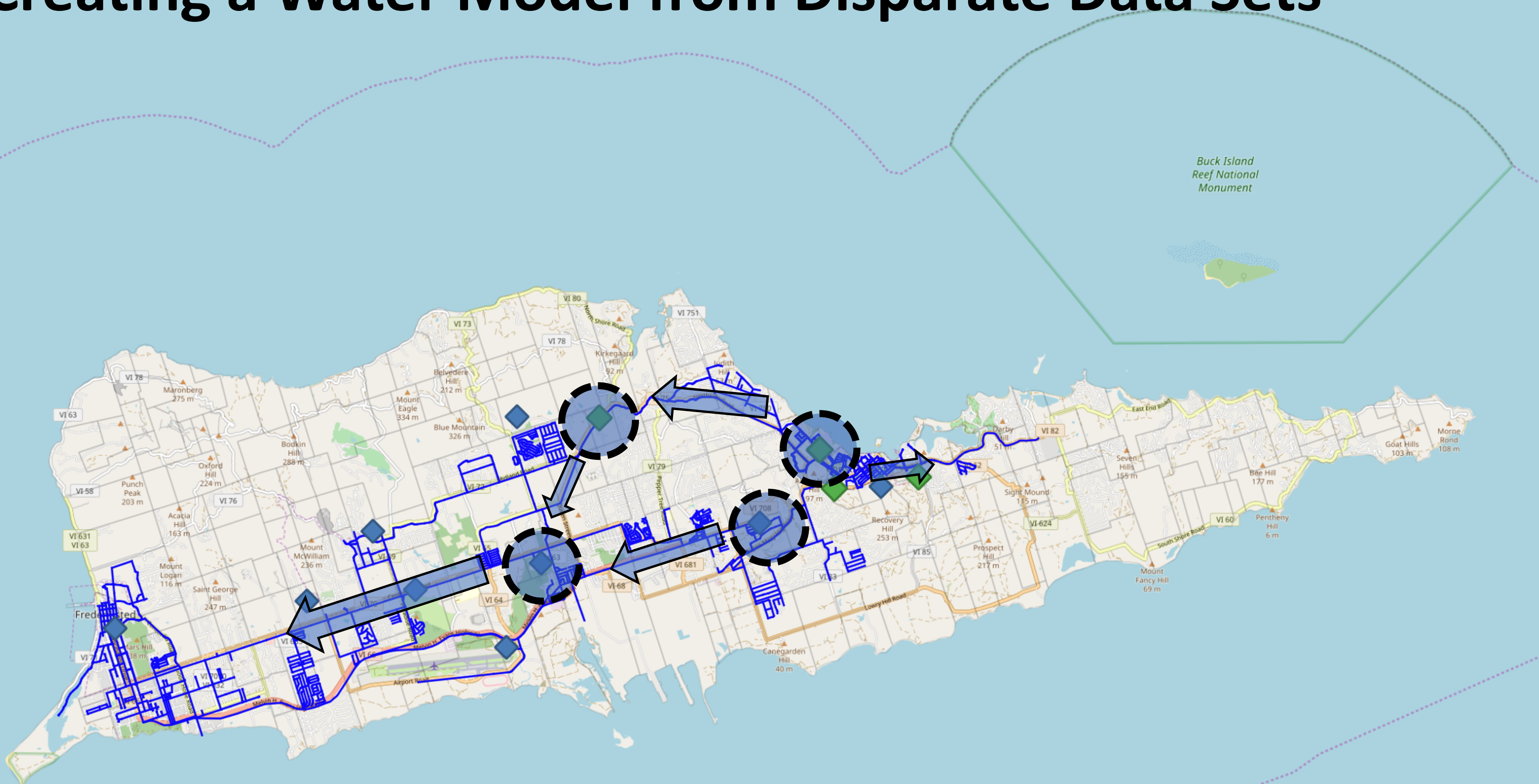
Fixing Electric Power Models for Analysis



Issues with Electricity Utility Data

- Incorrect per-unit voltage for infrastructure
- Recirculation issues (mislabeled delta & wye transformers)
- Customers outside normal voltage constraints

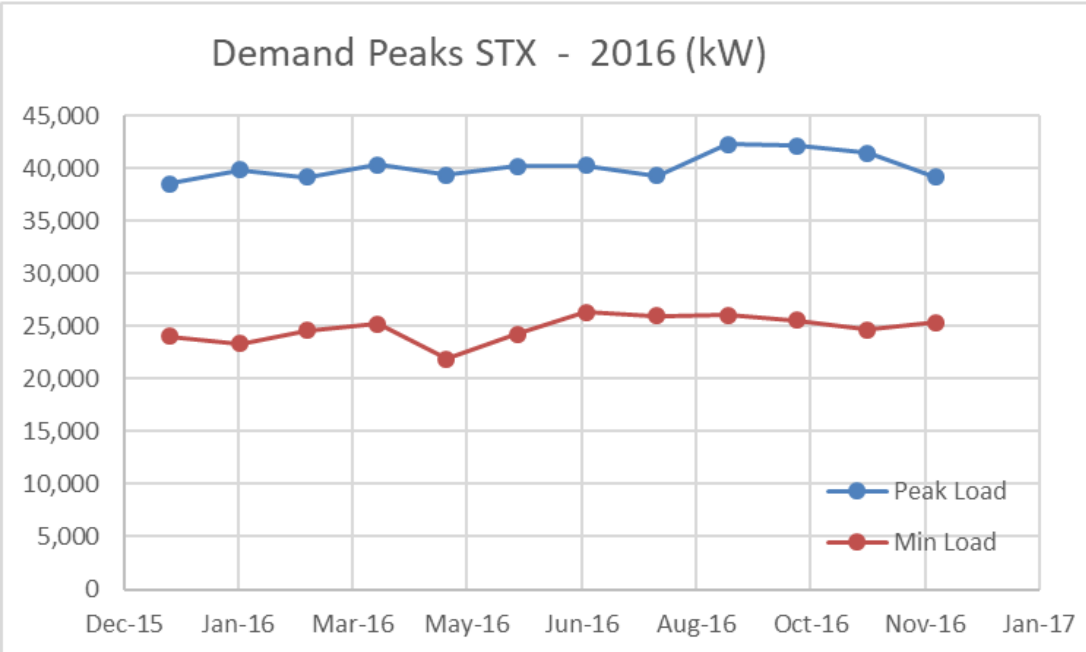
Creating a Water Model from Disparate Data Sets



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

Generation – Oversized and Inefficient

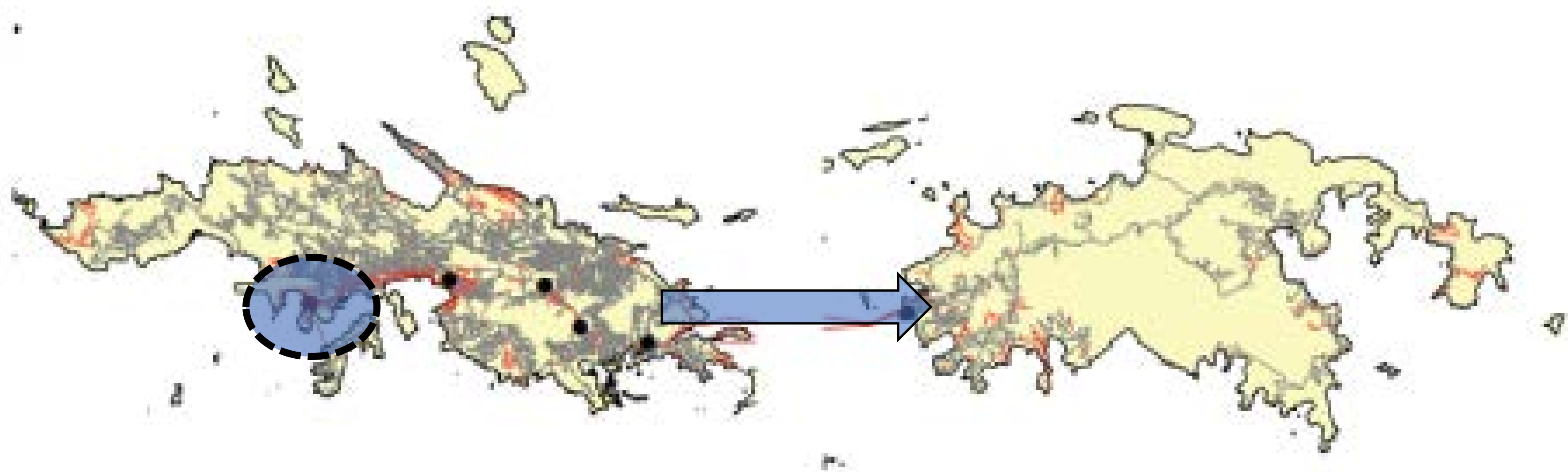


Gas Turbine Generators STX Power System			
Unit	Fuel Type	Capacity (MW)	Unit Type
10	#2 Fuel Oil	10	Worthington STG
11	#2 Fuel Oil	19.1	GE STG
16	Dual (#2 or LPG)	20.9	GE MS5001P CT
17	Dual (#2 or LPG)	21.9	Alstom
19	Dual (#2 or LPG)	22.5	GE5001
20	Dual (#2 or LPG)	22.5	GE5001

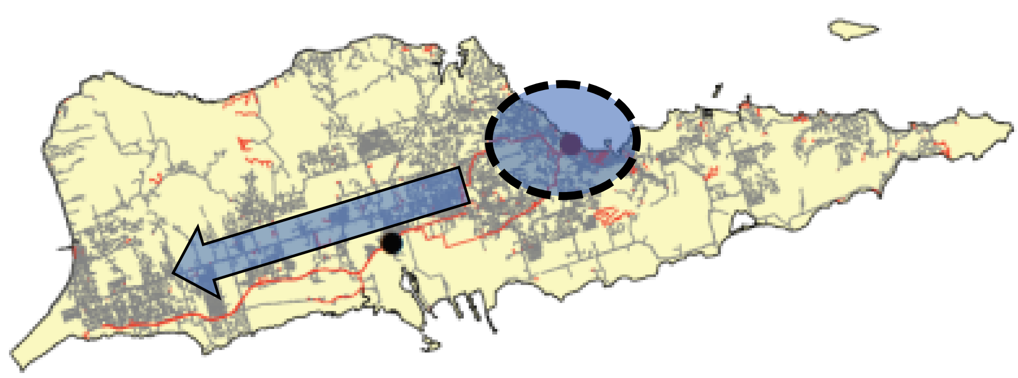
Blackstart Emergency Generators			
Unit	Fuel Type	Capacity (MW)	Unit Type
--	#2 Fuel Oil	0.75	GE6F09802

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

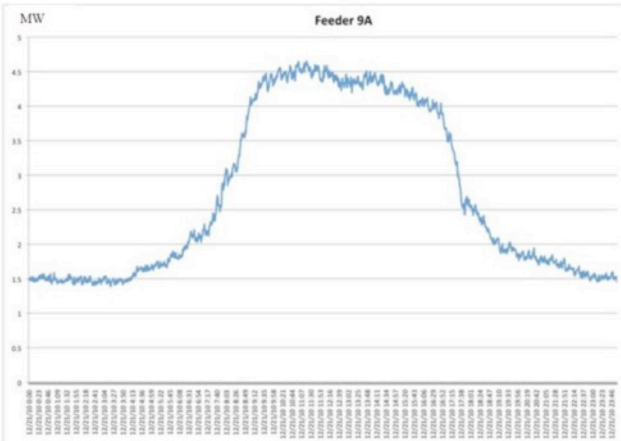
Transmission & Distribution –
Single Generation Plant Leaves Communities Vulnerable



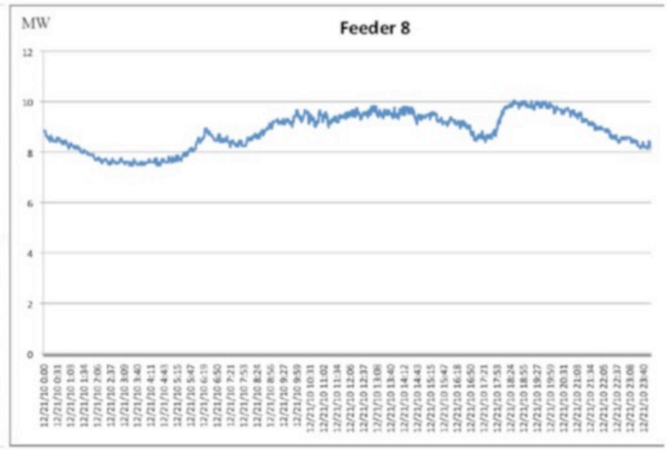
- Centralized electricity Production
- Aging generation, transmission, and distribution infrastructure



Critical Loads – (Mis)match with Community Needs

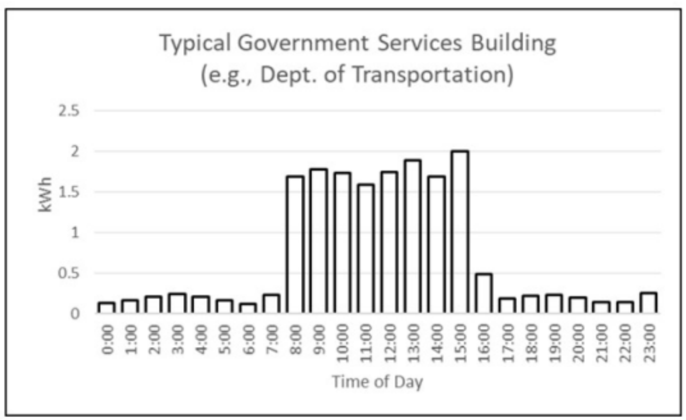


(A)

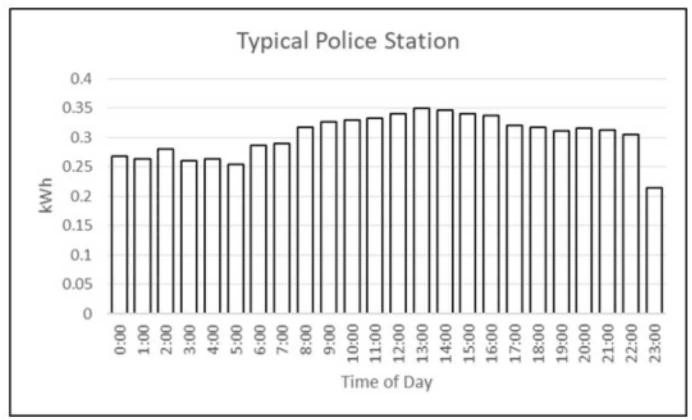


(B)

- Community industrial / commercial and residential loads have regular characteristics



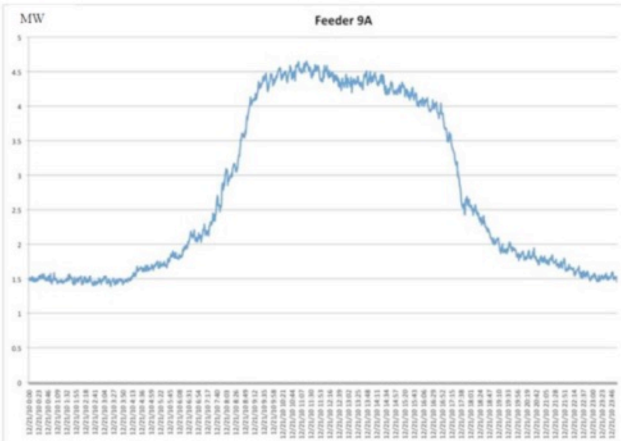
(A)



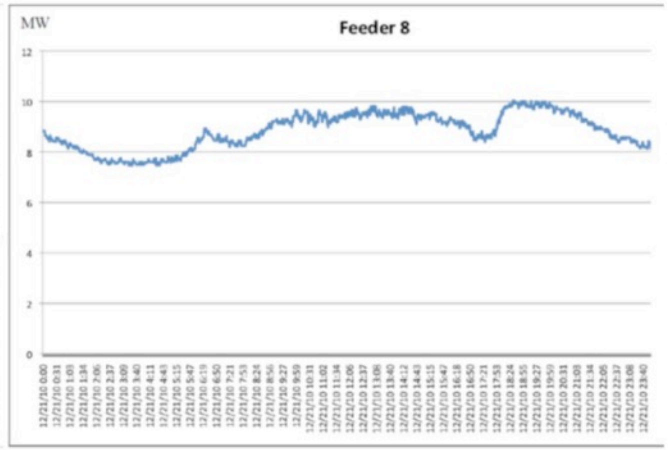
(B)

- Some critical loads match community needs

Critical Loads – (Mis)match with Community Needs

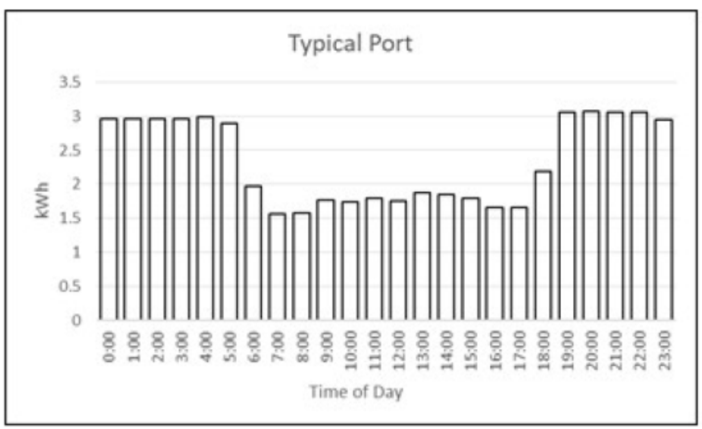


(A)

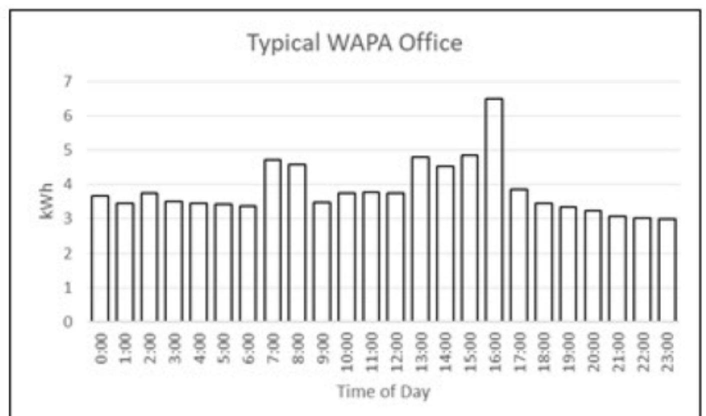


(B)

- Community industrial / commercial and residential loads have regular characteristics



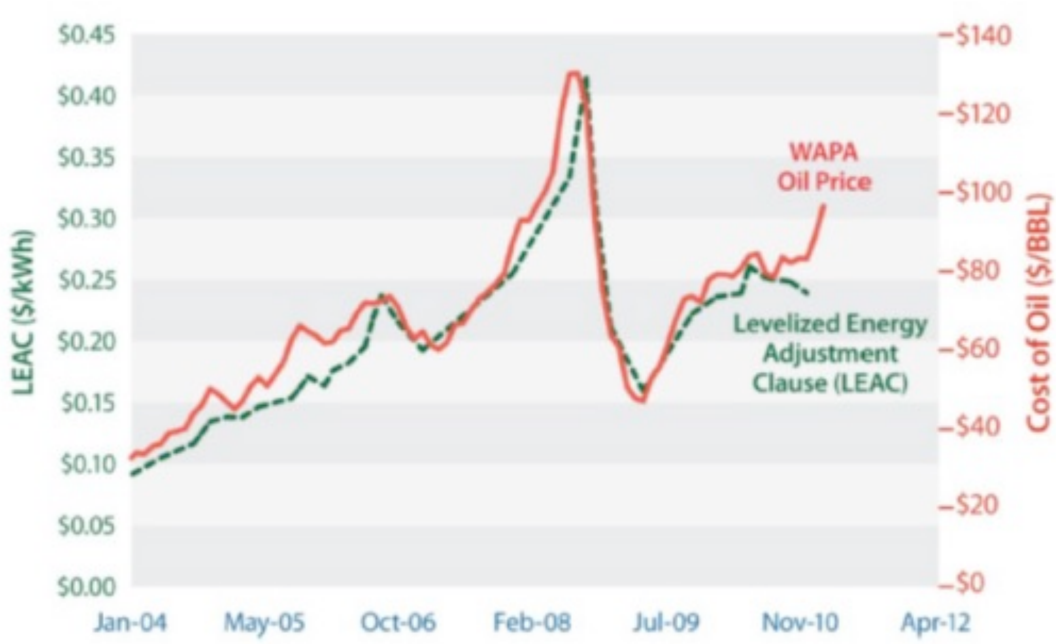
(A)



(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